ECL 197

ENGINEERING CASE STUDY
FROM THE ELECTRIC POWER INDUSTRY

STEADY STATE THERMAL RATINGS

FOR

220 KV OVERHEAD CONDUCTORS

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ECL 197A

STEADY STATE THERMAL RATINGS FOR 220 KV OVERHEAD CONDUCTORS

Part A

The Problem

Written by B. Vincent Viscomi with the support of the Middle Atlantic Power Research Committee. Published by the Engineering Case Program with the support of the National Science Foundation.

PREFACE

This case study represents an actual situation which took place in the Pennsylvania Power and Light Company. It reveals some of the important facets which seem to be common to many, if not all, engineering problems.

The first of these is the uniqueness of the specific situation. Although the problem of conductor thermal capability had been worked on by others, their results could not be applied directly to the PP&L system because of PP&L's own particular line design, weather conditions, and geographical location.

The second is the need to make assumptions and to test the effects of the assumptions on the final result. In this instance, assumptions were made with regard to solar absorption, radiation emissivity, hours of operation above annealing temperature, and others. These all were rather conservative, but nonetheless the study results made with these assumptions permitted a much more liberal line loading than had been allowed prior to the study.

Finally, there is always the need for balancing opposing parameters--trading off one feature for another, as it were. In this study, compromises had to be made between thermal loading and conductor annealing, between line design and emergency overload frequency and duration, between benefits of increased line loadings and costs of increased line losses.

The approach used in solving the problem described in this case study--specifying its uniqueness, making valid assumptions and reaching acceptable compromises--can be adapted to the solution of many other engineering problems.

E. F. Reis
Pennsylvania Power
and Light Company

INTRODUCTION

In 1958, Jack Roth, as a project engineer in the System Planning Division of Pennsylvania Power & Light Company, was involved in the forecasting of loads on the transmission lines of the company. These studies are attempts to predict one to five years in advance the current flow in the many lines of the company's transmission system.

It was the function of the System Planning Division to develop plans for the orderly expansion of the electrical system to include the establishment of the need and location of additional facilities, determining voltages and obtaining the rights of way. This information would then be given to the Transmission Section of the Electrical Engineering Department which had the responsibility for the electrical and structural design of the power lines.

However, land costs and the costs of stringing new lines for transmission lines, primarily land costs, were becoming extremely expensive, and there was a resulting economic motivation to make maximum use of existing lines and rights of way. Jack said, "It seems that every time we plan a new transmission line, the land costs immediately skyrocket along the proposed right of way. This, added to the litigation costs which are also increasing, leads to exorbitant costs per mile for system expansion."

His analysis showed that loads very close to or exceeding manufacturer's ratings could be expected on many of the transmission lines in the very near future. Normally, under these conditions, the planning of new lines would be initiated. However, due to the greatly-increased costs of new transmission lines, Jack was asked to consider alternative solutions to the problem.

Jack was aware that the manufacturer's ratings were conservative; in fact, some of the adjoining utilities used ratings for their lines which exceeded the manufacturer's recommendations. However, if plans for system reinforcement were not initiated, difficulty in obtaining approval for the "overloaded" lines from the Operating Department was anticipated. Indeed, when the Operating Department was contacted, they informed System Planning that the Operating Department would not operate any line above the existing rated load until they were convinced this was a safe procedure, and new maximum ratings were established.

Jack Roth attended several meetings held in the System Planning Department to discuss methods of rating lines. It was noted that the manufacturer's ratings were obtained on the basis of thermal calculations. High voltage transmission lines are not normally limited by voltage drop considerations but, rather, by the increase in temperature of the wire resulting from the I^2R losses. The problem is basically one of heat balance--the heat gain due to the I^2R loss plus solar radiation, must equal the heat dissipated by convection and radiation, in the steady state. In this analysis, the resulting temperature of the wire is of utmost importance. With increasing temperature, annealing of the wire will take place.

Annealing characteristics of copper and aluminum are well known. Annealing means loss of strength, and it occurs whenever the copper or aluminum is heated above roughly 100°F. It is a time-dependent phenomenon and occurs at a very slow rate at 100°F but accelerates quite rapidly as the temperature of the conductor increases. Annealing is also a cumulative effect; during cyclic temperatures, the amount of annealing depends upon the operation time at high temperature and the resulting loss in strength will not be regained when the temperature is reduced. (Some typical annealing curves are presented in Figure 1A, Appendix A.)

One other point concerning this loss of strength should be noted--the mechanical strength of an electrical conductor is usually put to its most severe test in winter time, when there are heavy winds and sleet or ice loadings on the conductor. On the other hand, the loss of strength due to operation at elevated temperatures is most likely to occur in the summer time with high ambient temperatures and heavy electrical loads on the lines. Thus it is possible for a line to suffer a severe loss of strength in the summer time but actual failure would not take place until the following winter!

Returning again to the determination of the temperature of the conductor, we see that the principal mechanism for heat dissipation is forced convection which is primarily dependent upon atmospheric temperature and wind speed for a given conductor. Although the manufacturer's ratings were obtained on the basis of thermal calculations, they provided but a single rating for each conductor for the entire country, thereby ignoring the variations in thermal environment. When Jack heard this he exclaimed, "You mean the rating would be the same in Alaska and the Arizona desert!"

At several of the meetings, Jack had a definite impression that some of the participants felt they were wasting their time discussing thermal ratings. They felt that the manufacturer's ratings were conservative, therefore had a factor of safety and this was desirable. The only way Jack was able to keep the discussion open was to note a neighboring utility used ratings considerably in excess of manufacturer's ratings and had not experienced any difficulties.

It was finally decided to proceed with the analysis of the problem, and the Electrical Research Section of the Electrical Engineering Department was asked to render assistance. Ed Reis, a young engineer in this section, was assigned to the project.

JACK ROTH AND ED REIS

Jack Roth graduated from Bucknell University in 1952 and obtained his master's degree from Lehigh University in 1963--he was working part-time toward his Master's degree at the time of this project. After graduation from Bucknell, he joined the IBM Corporation. About six months later, Jack found it necessary to resign his position to assist in the management of a family-owned business. After approximately one year, the difficulties in the business cleared up and in July, 1954, Jack joined PP&L.

In October, 1955, at the completion of the company training program, he was assigned to the Transmission Planning Section of the System Planning Department. In Jack's words, "I was one of two project engineers in this section and, therefore, had a 50% chance of getting any particular job that came into the section. This is about how I view my assignment to the thermal rating study." Jack further explained that he was convinced it would be safe to operate certain transmission lines above the manufacturer's ratings but the Operating Department was adamant in their refusal to operate the lines above these values. They would have to be convinced!

Ed Reis, a 1956 graduate of Lafayette College, had just received his MSEE degree from Lehigh University. He worked for PP&L during the summers prior to his junior and senior years at Lafayette and joined them on a full-time basis after graduation. From 1956 to 1958 he was assigned to the Substation Design Section of the Electrical Engineering Department and, after obtaining his master's degree, was transferred to the Electrical Research Section. "The function of the Electrical Research Section is to explore

and evaluate new energy sources, equipment, and products as well as to work on nonroutine and unusual problems of an engineering nature. Although my degrees are in electrical engineering, I welcomed the opportunity to expand my knowledge by getting involved in this project, which is essentially mechanical in nature," Ed said.

The project was given a high priority, but it was understood that Ed would not work full time on the thermal rating as he was at that time involved in two other projects.

PENNSYLVANIA POWER AND LIGHT COMPANY

The PP&L Company serves a 10,000 square mile area in Central-Eastern Pennsylvania, with headquarters in Allentown, Pennsylvania. It is an investor-owned public utility and is a part of a large power pool known as the Pennsylvania-New Jersey-Maryland (PJM) Interconnection, composed of 13 companies serving an area of 48,700 square miles. PP&L produces electric power from five steam, three hydro-electric and nine combustion-turbine generating stations, and can purchase power from or sell power to neighboring utilities via the PJM Interconnection.

Figure 2A, Appendix A, shows the main PP&L power supply system and interconnections as of 1974, including projected system expansion. At the time of this project, 1958-60, the highest transmission voltage used in the system was 220 KV (kilovolts).

PROBLEM DEFINITION

As Ed and Jack sat down to define the scope of the study they agreed that, initially, they would attempt to determine the current carrying capacity of all the 220 KV lines on the system. The thermal limitations of terminal equipment and line accessories such as conductor clamps and disconnects were not to be included nor was consideration to be given to limitations imposed by voltage drops or system stability.

In approaching the problem, they considered the following to be the key considerations:

1. What methods were available to evaluate the heat loss from a cylindrical surface under outdoor conditions?

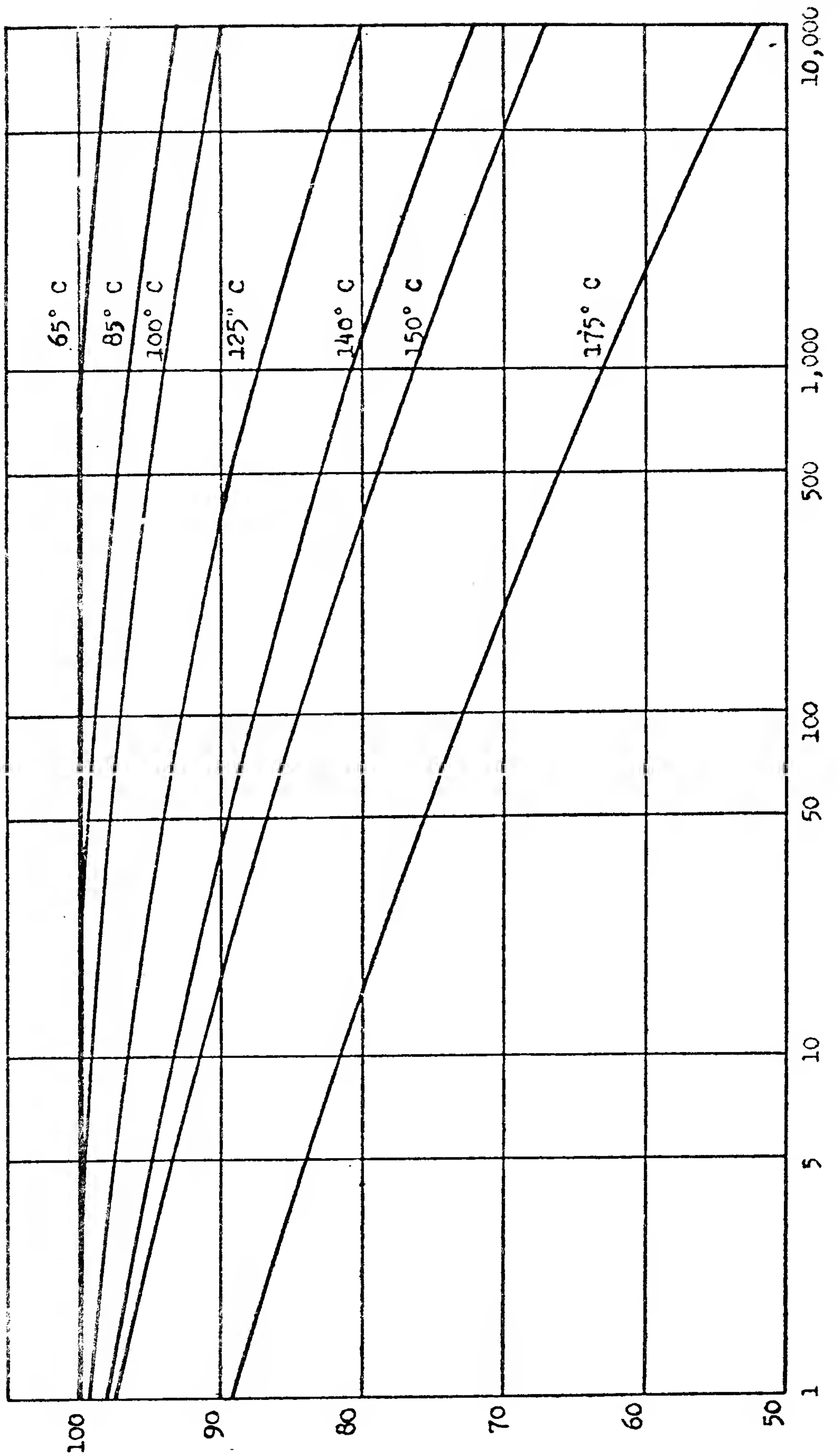
2. What were the wind conditions and ambient temperatures prevailing on the PP&L system? Were they similar to the values used in determining the manufacturer's rating?

3. How significant was the solar radiation heat gain? If solar heat gain had to be considered, separate calculations would be required for each line to include its orientation.

4. At what temperature could the transmission lines operate? This would be a function of their annealing characteristics and also of the construction of the line. The common type of conductor used in 220 KV transmission is ACSR (aluminum cable with steel reinforcement). If the temperature of the aluminum exceeded 100°F, annealing would take place; however, no annealing of the steel would take place in the operating temperature range of the conductor. Therefore, the annealing curve of ACSR would be a composite of the aluminum and steel and would depend on the ratio of the two materials used in the conductor. (Figure 3A shows a cutaway view of an ACSR cable.)

APPENDIX A

Typical Thermal-Time Characteristics of an Aluminum Conductor



Heating Period in Hours

Per Cent of Initial Ultimate Strength

Figure 1A

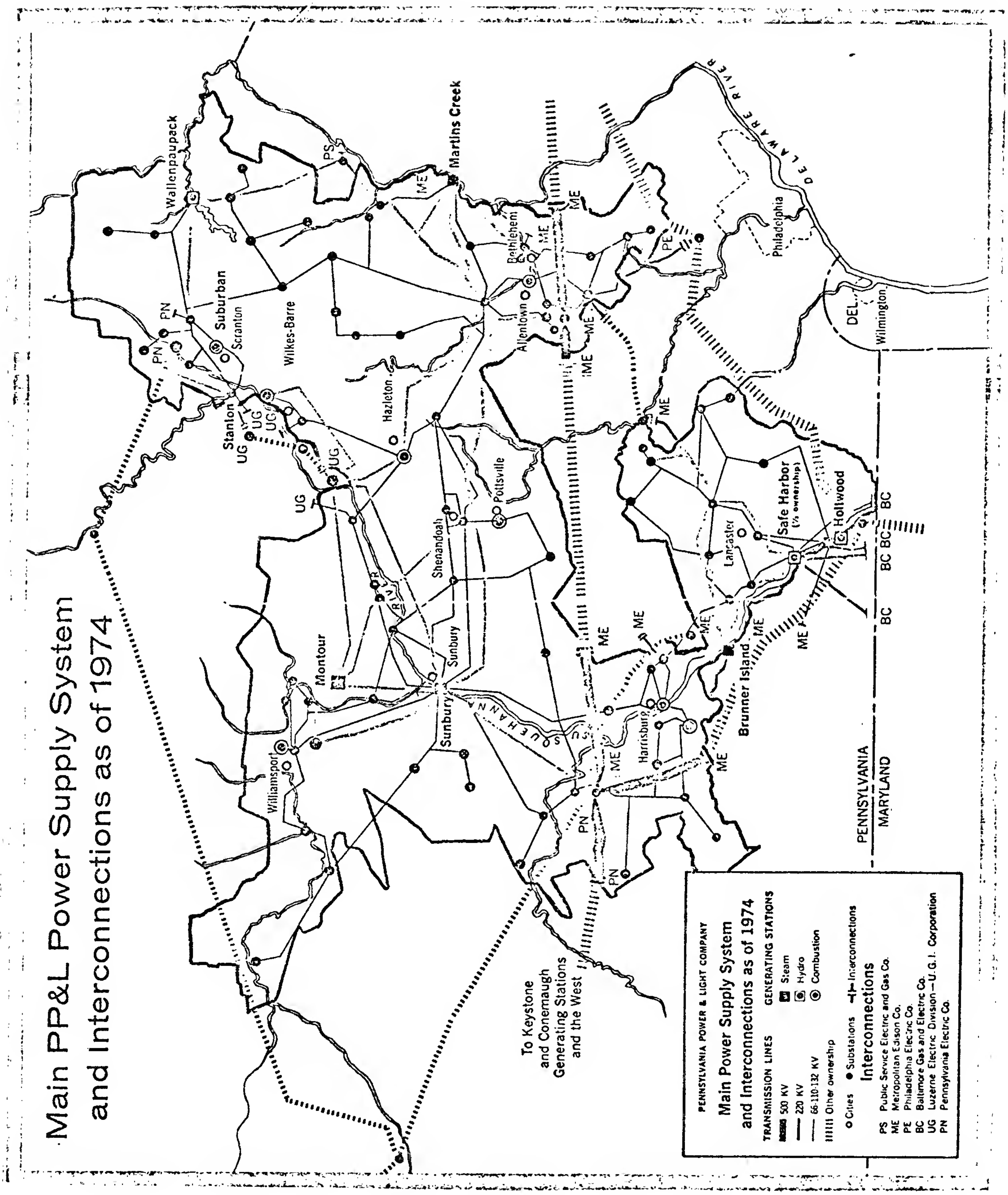

Main PP&L Power Supply System
and Interconnections as of 1974
Wallenpaupack
Martins Creek
Suburban
Scranton
Wilkes-Barre
Bethlehem
Allentown
Hazleton
Stanton
Pottsville
Shenandoah
Montour
Sunbury
Williamsport
Harrisburg
Brunner Island
Lancaster
Safe Harbor
Holtwood
Philadelphia
Wilmington
DEL.
DELAWARE RIVER
SUSQUEHANNA
PENNSYLVANIA
MARYLAND
To Keystone
and Conemaugh
Generating Stations
and the West
PENNSYLVANIA POWER & LIGHT COMPANY
Main Power Supply System
and Interconnections as of 1974
TRANSMISSION LINES
500 KV
220 KV
66-110-132 KV
Other ownership
GENERATING STATIONS
Steam
Hydro
Combustion
Cities
Substations
Interconnections
Interconnections
PS Public Service Electric and Gas Co.
ME Metropolitan Edison Co.
PE Philadelphia Electric Co.
BC Baltimore Gas and Electric Co.
UG Luzerne Electric Division—U.G.I. Corporation
PN Pennsylvania Electric Co.

Figure 2A

Figure 3A

Steel-reinforced aluminum conductor, 19 steel strands, 30 aluminum strands.
(Aluminum Company of America)

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STEADY STATE THERMAL RATINGS FOR 220 KV OVERHEAD CONDUCTORS

Part B

The Solution

THE LITERATURE SEARCH

"As you would expect, my first approach to this problem was to conduct a search of the literature. Jack Roth gave me a lead on a paper published by two engineers at Philadelphia Electric Company, a neighboring utility. This paper was the basis for the ratings established by PE Company, which exceeded the manufacturer's values. Jack viewed the PE ratings with envy!" Ed Reis remarked. He continued, "I also located an article dealing with thermal rating in Electrical World authored by Mr. H. A. Enos of the American Gas and Electric Service Corporation. Interestingly, both of the papers were published in 1943. As you will recall, in 1943 the country was engaged in World War II and there was a severe scarcity of copper, the conductor material used almost exclusively at that time. Consequently, there was a great deal of interest in determining the maximum current that could be safely carried on existing conductors. The incentive existed to get all they could out of their lines! Apparently, as a result of the post-war boom and the switch from copper to aluminum as the primary conductor material, little use was made of this information."

The article by Mr. Enos is included in Appendix B as Reference 1B. The heat balance equation used by this author is that, in the steady state, the heat gain due to the I^2R loss plus solar radiation must equal the heat loss by convection plus radiation or:

$$I^2R + W_s = W_c + W_r$$

where I = Current amps
R = Resistance of wire per unit length, ohms/ft
W_s = Heat gain due to solar radiation, watts/ft
W_c = Heat loss by convection, watts/ft
W_r = Heat loss by radiation, watts/ft.

The formulae used by Mr. Enos for the heat gain and losses are in the appendix and will not be duplicated here. He considered them to be the most complete and accurate formulae available at the time. They were obtained from the International Critical Tables, published in 1929, and the "classic" heat transfer text by McAdams, published in 1942.

In considering the heat loss by convection, Mr. Enos included expressions for both natural and forced convection; and for heat loss by radiation, expressions for dissipation to the earth and to the sky. The author recommended his procedure rather than, in his words, "some short-cut method."

The Philadelphia Electric Company paper, entitled "Ampere Load Limits for Copper in Overhead Lines," was presented to the American Institute of Electric Engineers, now the Institute of Electrical and Electronic Engineers, by Messrs. A. H. Kidder and C. B. Woodward in 1943. The heat balance used in this paper was the I^2R loss in the conductor equaled the heat dissipation by forced conduction and radiation or, as presented by the authors:

$$I^2R = WS$$

where W = Heat dissipated by radiation and forced convection, watts/in^2

S = Surface area of a given length of conductor, in^2.

The authors of this article considered the effect of solar radiation to be insignificant. They also used a single expression for radiation heat loss--Mr. Enos presented two--and only considered forced convection. The authors were able to reduce the problem to the following expression for the ampere carrying capacity:

$$I = CK\,d\,\sqrt[4]{d + 2s}$$

where C = Residual factor

K = Atmospheric factor

d = Conductor diameter

s = Conductor cover thickness.

(This article is included in the appendix as Reference 2B on page 6B; the expressions for K and C are included there.) The atmospheric constant depends on wind velocity, atmospheric temperature, and conductor surface temperature. The residual factor contained convection and radiation constants as well as wind speed and conductor and ambient temperatures. Messrs. Kidder and Woodward were able to show that C was practically a constant for the conductor sizes, wind velocities and temperatures used in the study. Therefore, within five percent error, the problem could be reduced to the determination of the atmospheric factor, K. Using U. S. Weather Bureau data to obtain <u>simultaneous</u> values of temperature and wind speed, the atmospheric factor was determined for a given conductor temperature. Since the object is to carry a high load at the lowest possible conductor temperature, the worst ambient condition is the

combination of high temperature and low wind speed. However, the authors found that maximum ambient temperature was not coincident with minimum wind speed! The maximum ambient temperature of 40°C (104°F) was accompanied by an 11 miles per hour wind. The worst condition, lowest value of K, found in their study was a temperature of 23°C (74°F) and a wind speed of one mile per hour.

The equations used for forced convection and radiation loss in Messrs. Kidder and Woodward's paper were obtained from an article published in the General Electric Review in 1930 authored by Messrs. O. R. Schurig and C. W. Frick. Mr. Enos questioned the validity of the assumptions as well as the accuracy of these equations, and the written discussion of the Philadelphia Electric Company paper reveals an exchange between Messrs. Enos and Kidder. (The written discussion is also included in Appendix B, page 11B.)

THE METHOD

After Ed and Jack had reviewed the two papers and traced each equation back to its source, they decided to use the relationships presented in the article by Mr. Enos. Although Mr. Enos strongly recommended that heat loss by radiation and solar heat gain be included in the analysis, they were reluctant to do so. If solar heat gain were to be included, separate calculations would be required for each line to consider its orientation. The solar heat gain also depends on the time of day, presence of cloud cover and the emissivity of the line. Ed said, "Mr. Kidder ignored solar heat gain but included the heat dissipated by radiation. This was a non-conservative assumption--the actual temperature of the lines would be higher than his predictions. As Jack and I were kicking this around, I sat down and calculated the heat gain by solar radiation at high noon on a clear day for a line running east-west and compared this to the heat lost by radiation." He found the heat lost by radiation to be greater than that gained by solar radiation and concluded he would be conservative in his ratings if he ignored all radiation. Consequently, the heat balance reduces to the situation in which the heat gained due to the I^2R loss equals the heat loss by convection. Ed used the expression for forced convection given in the article by Enos and simplified it to obtain:

$$I^2R = \frac{1.7 \times 10^{-4}\ (T_c - T_a)\ (T_c + T_a)^{.754}}{\log_{10} \dfrac{.000305\ (T_c + T_a)}{(VD)^{.57}} + 1}$$

where I = Current in amperes
R = Conductor resistance, ohms per foot
T_c = Conductor temperature, degrees Kelvin
T_a = Ambient temperature, degrees Kelvin
V = Wind speed, feet per second
D = Conductor diameter, inches.

Ed called the right hand side of the above expression the weather factor, K, similar to the procedure used in the PE Company report. For a given conductor, Ed's weather factor also depended upon the ambient temperature, the wind speed, and the conductor temperature--K is simply the I^2R loss per foot of conductor.

The problem now confronting Ed and Jack was to obtain working values of these parameters. They felt that reasonable values of conductor and ambient temperatures could be obtained without too much difficulty but pondered over the assumption of wind velocity. Ed mentioned to Jack that the manufacturer's usual assumption was a wind speed of two feet per second. Jack spread his hands approximately two feet apart, blew softly and exclaimed, "Two feet per second is hardly any wind at all!" Shortly thereafter, Jack stopped to see Ed and noticed a mound of paper on his desk. Ed had decided to analyze Weather Bureau data for the PP&L system in order to determine the most severe operating conditions for the system lines. The mound of paper represented three years of weather records in the form of hourly temperatures and wind speeds from the Allentown-Bethlehem-Easton Airport, Scranton and Harrisburg, Pa.

However, in analyzing the records Ed discovered that, at times, the wind speed at the weather station is insufficient to spin the anenometer and the symbol C, for calm, is reported. Ed and Jack's procedure only included forced convection and therefore, the C's represented a problem. Ed thought, "Since the conductor is at a higher temperature than ambient, natural convection currents will be set up, and I should be able to use this velocity during calm conditions. What I did was to calculate the free convection heat loss, using the equation in Enos' report, and then determined what wind speed in the forced convection equation would yield the same heat loss. The calculations indicated the equivalent velocity was approximately 1/2 foot per second. Consequently, for those hours when 'calm' was recorded in the reporting forms, I inserted the value 1/2."

With this problem solved, Ed then wrote a computer program to calculate K and obtain a frequency distribution curve for various conductors for the winter months November,

December, and January, and the summer months June, July, and August. The conductor temperature assumed for these calculations was 100°C. (A typical curve is shown in Appendix B, Figure 1B.)

The conductor temperature of 100°C was close to the 200°F (93°C) design temperature recommended by the manufacturer of stranded aluminum and ACSR conductors. However, Ed and Jack were interested in obtaining the current carrying capacity on the few days of the year when ambient conditions gave poor heat removal; i.e., it would be necessary to determine the <u>maximum</u> safe operating temperature of the conductor.

FINAL ENGINEERING CONSIDERATIONS

Ed was aware that, when a conductor is operated above its design temperature, two factors to be considered are:

1. The thermal expansion resulting from high temperature operation will increase the sag of the wires. It is possible that the conductor clearance may be reduced below minimum safety requirements as specified by the National Bureau of Standards.

2. High temperature operation may cause a loss of conductor tensile strength--annealing. (The annealing problem was discussed in Part A and Figure 1A shows typical annealing curves.) Briefly, the cumulative time of operation at elevated temperatures must be considered in determining how much annealing has taken place.

To obtain additional information on these two points, meetings were held with representatives of two companies--Aluminum Corporation of America (Alcoa) and Anaconda Wire and Cable Company. Jack wanted the manufacturers to discuss the characteristics and to provide maximum operating temperatures of their conductors. Because of the many variables involved in line construction, conductor size, minimum clearances, and allowable loss of strength, neither company would make recommendations concerning the maximum operating temperature for transmission line conductors. However, they presented various curves which show the relationship between loss of strength, operating temperature and time for conductor grade aluminum and copper.

Figure 1A, discussed previously, was obtained from Alcoa. From this figure, it is seen that annealing begins

at a temperature slightly above ambient temperatures for aluminum, but at 100°C there is only a 10% loss in ultimate strength in 10,000 hours.

On the other hand, the strength of the steel core in ACSR conductor remains essentially constant up to about 450°C (842°F). Therefore, the annealing curves for ACSR conductor are a composite of annealing curves for steel and aluminum dependent upon the ratio of aluminum to steel strands in the cable. Calculations for one of the common cables used on the PP&L system showed that a 20% loss of strength in the aluminum strands resulted in an 11% loss of strength in the complete cable. With this information and the annealing curves, Ed saw that an increase in the maximum conductor temperature to 125°C would decrease the strength of the cable less than 11% in 10,000 hours.

To determine the probable amount of conductor annealing he decided to determine the number of hours per year that a typical line would operate at annealing temperatures. At Ed's request, the System Operating Department prepared load duration curves for several 220 KV and 66 KV transmission lines. (Figure 2B shows the 220 KV line loadings for the summer of 1958.) Using these curves, Ed obtained the number of hours of operation per year at annealing temperatures by assuming that the probability of a low weather factor occurring simultaneously with a high line loading is the product of the probability of each occurring independently. The results indicated a total of approximately 36 hours per year at conductor temperatures between 80°C and 125°C. On this basis the conductor would have to operate for about 300 years to obtain 10,000 hours of annealing time, obviously well beyond the useful life of a transmission line! Considering 50 years of useful life for a line, the loss of strength was estimated at less than five percent.

Finally, all existing 220 KV lines on the system were reviewed by the Transmission Section of the Electrical Engineering Department to determine if any of the following considerations would be the limiting factor in establishing a maximum conductor temperature:

1. Increase in sag at higher temperature causing either reduced ground clearances or reduced clearances to other lines.

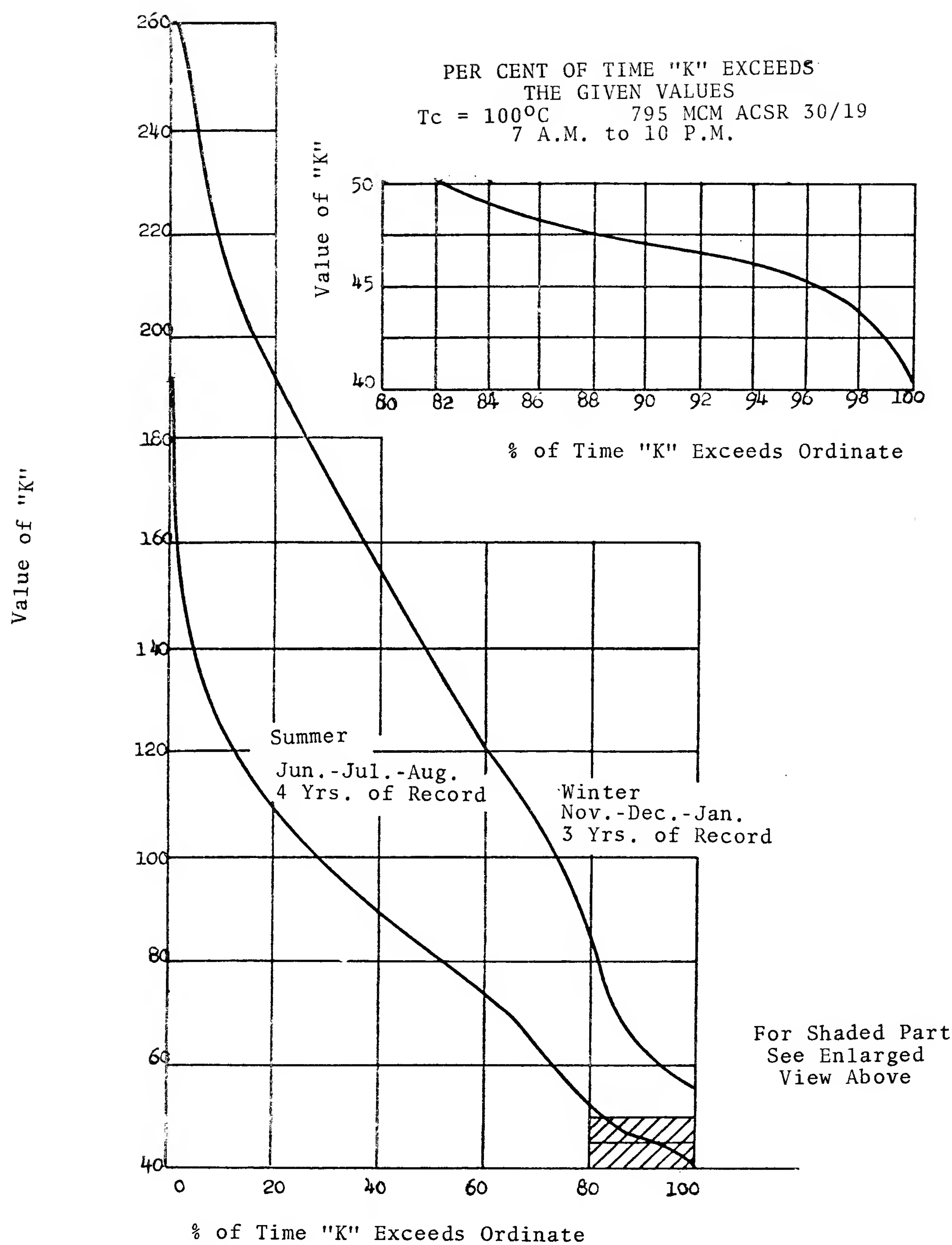
2. Localized heating in conductor clamps or splices.

3. Limitations in terminal equipment--switches, line traps, transformers, and so forth.

The lines erected prior to 1950 were found, with few exceptions, to be limited by the increased conductor sag when operating at higher temperatures. The maximum current for these lines had to be limited to a value which would produce a conductor temperature no greater than that allowed by minimum clearance requirements. In several lines, carrying capacity was limited by localized heating in magnetic type clamps or in line splices. Ed prepared a table for all 200 KV lines giving the maximum operating current under summer and winter conditions. This table also included suggested construction changes to increase the capacity of the lines limited by sag, clamps or terminal equipment. This report was issued on July 13, 1960. (Portions of this report are included as Reference 3B beginning on page 16B of the appendix.) For the newer lines the ratings, as a result of this study, were increased approximately 40% for summer time operation and 60% for winter time operation. This significant increase in current carrying capability has deferred the need for new lines and postponed substantial capital expenditures.

Recognizing the need for additional conductor ratings in designing new lines and substations as well as obtaining maximum use from present facilities, a second report was prepared to include ratings for commonly used types and sizes of copper, aluminum, and ACSR base conductors, with an expanded temperature scale of 90°C to 180°C. This report was issued on October 17, 1960.

APPENDIX B



PER CENT OF TIME "K" EXCEEDS THE GIVEN VALUES
Tc = 100°C
795 MCM ACSR 30/19
7 A.M. to 10 P.M.
Value of "K"
50
45
40
80
82
84
86
88
90
92
94
96
98
100
% of Time "K" Exceeds Ordinate
Value of "K"
260
240
220
200
180
160
140
120
100
80
60
40
0
20
40
60
80
100
Summer
Jun.-Jul.-Aug.
4 Yrs. of Record
Winter
Nov.-Dec.-Jan.
3 Yrs. of Record
For Shaded Part
See Enlarged
View Above
% of Time "K" Exceeds Ordinate

Figure 1B

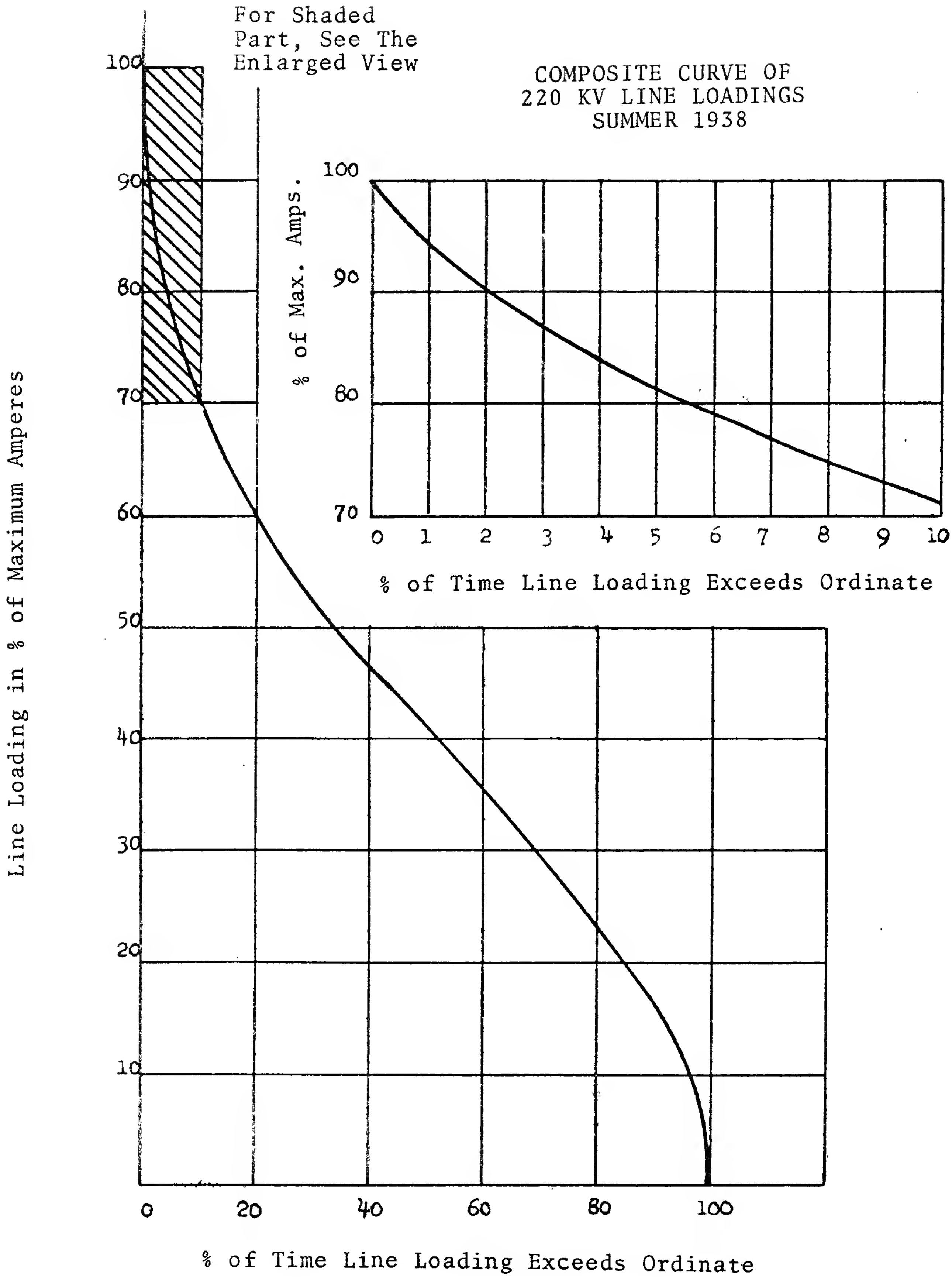

For Shaded
Part, See The
Enlarged View
COMPOSITE CURVE OF
220 KV LINE LOADINGS
SUMMER 1938
% of Max. Amps.
100
90
80
70
0
1
2
3
4
5
6
7
8
9
10
% of Time Line Loading Exceeds Ordinate
Line Loading in % of Maximum Amperes
100
90
80
70
60
50
40
30
20
10
0
20
40
60
80
100
% of Time Line Loading Exceeds Ordinate

Figure 2B

Current-Carrying Capacity of Overhead Conductors

Multiplicity of variables leads to basic formulas which cannot be replaced by simpler formulas without the sacrifice of accuracy — Formulas and application table presented for maximum utilization of facilities

H. A. ENOS, American Gas & Electric Service Corporation, New York, N. Y.*

SINCE the matter of current-carrying capacity of overhead conductors has become of such urgent interest under wartime conditions the author has studied the available data on which to base current-carrying capacity calculations. The desire to approach more closely the limiting values of current which might damage the conductor has brought about the necessity for the most accurate means of calculating the permissible currents. Until recently very little careful work has been done on this subject because of a lack of interest in it. However, interest in the heat transmission problems of mechanical engineering has stimulated careful research along that line which has produced quite accurate formulas which are equally adaptable to these electrical problems. Basic principles of heat conduction and radiation have been well known for quite some time. There is no disagreement among the various authorities as to the methods of calculation to be used for the usual applications.

Heat Dissipation

With regard to heat dissipation by convection the situation is not so fortunate. There are several theories as to the mechanism of convection and they are all difficult to express accurately in the form of formulas. This is primarily true because of the lack of sufficient experimental data. Formulas of this type which take proper account of all the factors involved are somewhat cumbersome, and one may be tempted to use the simplified approximate formulas which are presented in various texts. Those simplified formulas are quite satisfactory for cylinders larger than 1 in. in diameter, but, unfortunately, in the case of the usual sizes of wire they are quite inaccurate, the inaccuracies increasing rapidly with a decrease in wire size. The more complete formulas are recommended; they will not be found too burdensome.

Proper procedure in determining the current-carrying capacity of a bare conductor is first to decide upon the maximum allowable temperature for the conductor itself. Consideration should be given to the effect of temperature and its duration upon the strength or life of the conductor (this will be discussed in greater detail later in this article). The next step in the procedure is to decide as to the air temperature, wind velocity and earth temperature under which it is desired the conductor shall reach its maximum temperature.

Having made the foregoing assumptions, it is only necessary to substitute in the appropriate formulas those values together with the values of the factors which are dependent upon the kind and condition of the conductor. The heat balance for the equilibrium condition states that the watts generated in or absorbed by the conductor equals the watts dissipated from the conductor surface. Then the watts loss due to electrical resistance of the conductor plus the watts absorbed from solar radiation is equal to the watts dissipated from the wire by radiation and by convection.

Since an outdoor conductor usually has the possibility of having the sun shine upon it at the time of maximum current flow, the effect of the solar heat should be taken into consideration. Since the calculations easily show that its effect is considerable it cannot be safely ignored. Since also, its calculation is very simple there is no good reason for ignoring it. Some have concluded, as a result of tests which they have not properly interpreted, that the effect of solar radiation is negligible. The reader should not fall into the same error.

Radiation and Convection

In determining the amount of dissipation by radiation it is essential that it be calculated by the application of a suitable formula. There is a considerable difference between the formulas for radiation from a wire in a closed room and for radiation from a wire outdoors. Indoors the radiation takes place from the wire to the walls of the room and objects in the room. Temperature of the receivers of the radiation should be used in the formula and not the air temperature. Outdoors the radiation takes place partly to the sky and partly to the earth and adjacent structures. On account of the difference in the formulas for the two portions of the radiation they must be calculated separately.

In calculating the dissipation due to convection for outdoor conductors it is usually considered that some air movement is always present, however small. In that case the formula for forced convection should be used. It is based upon the direction of air movement being at right angles to the axis of the conductor. Of course there is always the possibility that the wind may blow parallel to the conductor at the time of maximum current. In that case the dissipation will be less, but no formula is available for calculating it. An approximation may be resorted to by consider-

*Distribution Engineer.

REFERENCE 1B

ing the wind to be crosswise but reduced in velocity, say by half. If one desires to be quite conservative with regard to this calculation of convection the velocity of the wind may be assumed at zero. In that case the formula for natural or free convection should be used.

Loss in Strength

It is desirable to refer again to the question of the maximum allowable temperature for the conductor. Even under wartime conditions it is usually thought best that the wire temperature should not reach a point or at least continue long at a point at which the wire might be permanently damaged. In the case of hard or medium hard drawn copper it is certain that it is undesirable to anneal the wire. Unfortunately it is not known definitely what combinations of temperature and time will just begin to anneal the wire. Too few tests have been made to determine those facts. Practically no tests have been made to determine the effects of heating under tension. There is some evidence that repeated cycles of heating and cooling have a cumulative effect, but the real extent is unknown. The effect of wire movement while hot is unknown and no correlation of change in elastic limit with change in ultimate strength has been made.

In view of the chaotic status of this problem at present it is not wise to propose radically higher operating temperatures, especially when adequate current-carrying capacities will be found for most wartime conditions with conservative values of conductor temperature. It is quite likely that past experience will show that a temperature of 80 deg. C. will not damage copper conductors under the usual loading cycles. Probably occasional short-time operation at around 95 deg. C. will not result in serious damage, although some tests have shown a slight reduction in strength after operating at 100 deg. C. for one hour. At any rate it is advisable to leave some margin to take care of transient overload conditions and short circuits.

In the case of weatherproofing covered conductors the calculations are much simplified by using the diameter over the braid as the diameter of the conductor in the formulas. This is entirely correct since all of the heat generated in the conductor by the current is conducted through the covering and is dissipated from the outer surface of the covering. It is necessary to assume a temperature for the outer surface of the covering which will be less than the maximum copper temperature by approximately the amount of expected temperature drop through the covering. With the usual copper temperatures the temperature drop may be taken as 10 to 15 deg. C. It is not necessary to know the exact temperature of the copper conductor, but it may be checked if desired by means of the conduction formulas (10) and (11). An error in assuming the copper temperature for the purpose of determining the conductor resistance is not serious because of the very small temperature coefficient of resistance.

Comprehensive Formulas

The author presents here the most complete and accurate formulas for wires which he has been able to find after careful study of the available data. It is recommended that these formulas be used rather than some short cut method. While they may seem complicated and difficult to use, that will not be found to be the case in actual use. Some may question why they have not been plotted into nomographic charts to simplify their use. It is doubtful whether satisfactory charts could be plotted from these complete formulas on account of the complex inter-relationships of the various factors. Even if such charts were plotted they would be complicated and just as difficult to use as the formulas themselves.

In using these formulas it is desirable to base all the calculations on a 1-ft. length of conductor. A slight variation in atmospheric pressure has very little effect upon the accuracy of the calculations and, therefore, it is advisable to assume this pressure at one atmosphere.

Heat Balance

$$I^2 R + W_s = W_c + W_r \text{ watts} \quad (1)$$

Solar Radiation Absorbed (1)

$$W_s = D\,L\,a\,S \qquad \text{watts} \quad (2)$$

Convection

(A) Dissipation by natural convection(2):

$$W_c = \frac{7.6 \times 10^{-6}\, T_a^{0.754}\, T_r\, A}{D \log_{10}\left(\dfrac{0.00438\, T_a^{0.57}}{D^{0.75}\, T_r^{0.25}\, P^{0.5}} + 1\right)} \text{ watts} \quad (3)$$

(B) Dissipation by forced convection(2):

$$W_c = \frac{7.6 \times 10^{-6}\, T_a^{0.754}\, T_r\, A}{D \log_{10}\left(\dfrac{0.00061\, T_a}{(PVD)^{0.57}} + 1\right)} \text{ watts} \quad (4)$$

Dissipation by Radiation—Outdoors (1) (3)

(A) Radiation to the earth:

$$W_{re} = 36.8\, e_1\, e_2\, F_e \left[\left(\frac{T_1}{1000}\right)^4 - \left(\frac{T_2}{1000}\right)^4\right] A \text{ watts} \quad (5)$$

(B) Radiation to the sky:

$$W_{rs} = 36.8\, e_1\, F_s \left(\frac{T_1}{1000}\right)^4 A \text{ watts} \quad (6)$$

(C) Total radiation $= W_r = W_{re} + W_{rs}$ watts (7)

(D) $F_e + F_s = 1.00$ (8)

Dissipation by Radiation—in a Closed Room (1) (3):

$$W_i = 36.8\, e_1 \left[\left(\frac{T_1}{1000}\right)^4 - \left(\frac{T_2}{1000}\right)^4\right] A \text{ watts} \quad (9)$$

Dissipation by Conduction Through Wire Covering (4)

(A) Heat Balance, $- I^2R = W_k$ watts (10)

(B) $$W_k = \frac{t_d}{0.01202\, r \log_{10}\left(\dfrac{D}{d}\right)} \text{ watts} \quad (11)$$

Nomenclature

A = Surface area of wire or its covering, if any, square inches = 3.1416 DL
a = Absorptivity of wire or covering, if any, for solar radiation.
D = Outside diameter of wire or covering, inches.
d = Inside diameter of wire covering, inches.
e_1 = Emissivity of wire or covering.
e_2 = Emissivity of earth or adjacent objects.
F_e = Fraction of total radiation directed toward the earth from wire.
F_s = Fraction of total radiation directed toward the sky from wire.
L = Length of wire of area = A, inches.
P = Atmospheric pressure, atmospheres.
R = Resistance of wire of length = L, ohms.
r = Thermal resistivity of wire covering.
S = Solar constant under prevailing conditions of time of day, time of year, latitude, elevation and atmospheric conditions, watts per square inch.
T_a = Average temperature of surface of wire or covering, if any, and ambient air, $= \dfrac{T_1 + T_2}{2}$, degrees Kelvin.
T_r = Temperature rise of wire, or covering, if any, above ambient air = $T_1 - T_a$, degrees Kelvin (also Centigrade).
T_a = Temperature of ambient air, deg. K.
T_1 = Temperature of wire or covering, if any, deg. K.
T_2 = Temperature of earth surface or adjacent objects, deg. K.
t_d = Temperature drop through ire covering, deg C.
V = Velocity of air movement, fee per sec.

Factor Values

Recommended values of the factors involved in the above formulas are given below. These values are the result of a careful study of all of the available information and it is believed that they will give results as close to accuracy as is possible with

present know[illegible]dge of these factors.

1. Absorptivity for solar radiation—a.

Oxidized copper	[illegible]
[illegible]ished copper	0.50
Weathered aluminum	0.60
Galvanizing—new	0.65
Galvanizing—weathered	0.75
Galvanizing—very dirty	0.91
Weatherproof covering	0.90

The above values were obtained from various sources, including: Kent's Mechanical Engineers' Handbook; U. S. Bureau of Stds. Bull. V. 7 and V. 9.; Proc. Phys. Society (London) V. 43.

2. Solar radiation constant—S.
(Derived from data in Tech. Paper No. 128, Bur. of Stds.) at latitude of Washington, D. C. on clear day at noon.
S in midsummer $= 0.612$ watts/ in.^{2}
S in midwinter $= 0.383$ watts/ in.^{2}

3. Emissivities—e.

Material	Value of e When Material Is		
	Highly Polished	Moderate Oxidized	Badly Oxidized
Copper	0.04	0.55	0.75
Aluminum	0.04	0.10	0.20
Zinc	0.04	0.23	0.28
Non-metallic all kinds	varies from 0.85 to 0.95; use $e = 0.90$		

The above values were obtained from various sources, including: Kent's Mechanical Engineers' Handbook; McAdams, "Heat Transmission" (McGraw-Hill Book Co., 1942).

4. Fractions of total radiation to earth, sky, etc., F_e and F_s. $F_e + F_s = 1.00$
For a round wire in the open with no objects higher than the wire, $F_e = 0.50$, $F_s = 0.50$
(Based on personal communication from Prof. W. J. Wohlenberg.)
If close objects such as buildings are higher than the wires the value of F_e should be increased somewhat.

5. Thermal resistivity of weatherproof covering. r. $r = 500$. (IPCEA value)

Wartime Current Ratings of Bare and Weatherproof Covered Copper Wires and Cables in Normal Operation. Current in Amperes

Wire Size A. W. G. or Cir. Mil.		Bare		Weatherproof	
		Summer	Winter	Summer	Winter
Solid	8	74	100	84	119
	6	99	135	110	160
	4	131	179	146	208
	2	176	242	189	269
Stranded	2	181	248	199	283
	1	215	297	237	338
	0	242	336	267	331
	00	282	391	308	439
	000	329	457	359	513
	0000	380	528	418	596
	250,000	423	591	468	683
	300,000	475	665	522	747
	350,000	525	757	582	830
	400,000	572	803	634	907
	500,000	658	926	734	1050

Table based on air temperatures 60 deg. F. (16 deg. C.) in winter and 110 deg. F. (43 deg. C.) in summer.

Maximum copper temperature 80 deg. C. and maximum temperature of braid surface 70 deg. C.

Do not use *winter* values if there is any possibility of the air temperature being above 60 deg. F. at time of maximum load.

Note that all of the I^2R loss is transmitted through the covering.

The current-carrying capacity table has been calculated by the use of the formulas given above. It is designed to cover normal operating conditions and not emergency overload conditions. No attempt has been made to set up ratings for emergency conditions because there is such a wide variety of loadings and durations that a single table would be extremely limited in its application. It would be better for the reader to calculate his own ratings for particular situations after deciding upon the limiting temperatures. This table has been bas[illegible] upon ea[illegible]n temperatures of 4 deg. [illegible] in the winter and 50 deg. C. in [illegible] summer. The wind velocity has b[illegible] assumed at 1 ft. per second c[illegible] wise of the wire. Conductor and [illegible] temperatures are given in the tab[illegible]

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5B

Ampere Load Limits for Copper in Overhead Lines

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Synopsis: The paper presents a method of determining approximately the maximum continuous current-carrying capacity of conductors in overhead lines, as fixed by certain operating limits of temperature and time, beyond which it is expected that the physical characteristics of copper conductors might be materially impaired. The paper deals illustratively with conditions in the Philadelphia area, but the method is equally adaptable to any situation.

The design limits of ampere ratings determined herein, are from 10 to 35 per cent higher for bare conductors, and from 10 to 20 per cent higher for covered conductors, than those previously used in the Philadelphia area. Operation at load equal to the design limit will, during 99.93 per cent of the hours in the average year, maintain copper temperatures below 100 degrees centigrade in normal operations and below 135 degrees centigrade in emergency operations.

UNDER ordinary conditions and particularly in the design of new single-purpose lines, there is little doubt that some sort of cost balance akin to Kelvin's law favors conductor sizes sufficiently large to give operating-temperature limitations a place of rather remote interest. Considerations of voltage variation and the advance provision for expected load growth in general-purpose distribution lines also favor the initial installation of conductor sizes considerably larger than the minimum that could be used if necessary.

The present emergency naturally compels a reconsideration of the design limits of conductor size, but not without a possibility of substantial future advantage to those central-station systems which will utilize the information thus gained to make the maximum use of an installed line-conductor size, rather than to abandon it in favor of an avoidable change to a larger conductor size. In the authors' experience there has been no instance where the natural cost balance that normally favors oversize conductors in new lines has been sufficient to offset the large expense that must be accepted when an otherwise adequate line conductor size must be abandoned in order to provide a larger size.

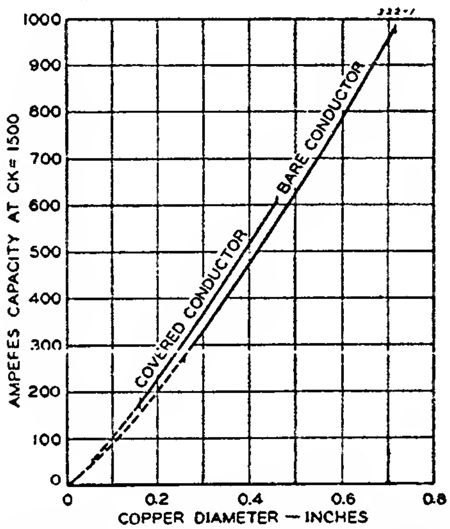

Figure 1. Principal effect of conductor diameter on ampere capacity of overhead lines

$$I = CKd\sqrt[4]{d+2s}$$

Line accessories such as conductor clamps and disconnects can have limitations that will become critical. Likewise, ... ances will need to be reconsidered at critical points, along lines which possibly might be required to operate at abnormally high conductor temperatures. Such limitations may be removed by thoroughly normal procedure and, usually, at much lower cost than to increase the conductor size. The working limits of the conductor material in its cooling medium must be known, however, before the other factors can be considered appropriately. This paper, therefore, centers its attention upon an approximate appraisal of present knowledge about the physical limitations of copper and a reconsideration of the natural heat-dissipating properties of conductors in overhead lines, as related to their effect upon the practical design limits of ampere loading for overhead lines.

Mechanical Limitations of Bare and Covered Copper

To the extent that copper may be said to have elasticity, then elasticity is the property of overhead line conductors which is most affected by temperature and time. Soft-drawn copper has very little and hard-drawn copper has the most but whatever elasticity is possessed by any conductor will be impaired to the extent that temperature and time may anneal the copper. The natural drawing effect which accompanies the mechanical stretching of copper imparts some measure of elasticity to it which it did not possess previously. Hence, mechanical tests of copper conductors, after partial annealing without mechanical stress may not be directly comparable to similar tests of identical conductors similarly heated, while kept under normal stringing tension. All of these factors contribute to a natural uncertainty that makes the mechanical characteristics of copper at comparatively low temperatures appear to be almost akin to the mechanical characteristics of alloy steels at much higher temperatures.

There appears to be considerable uncertainty, for instance, whether copper begins to anneal at 100 degrees centigrade or at 130 degrees centigrade. The range of uncertainty suggests, however, a probability that operating temperatures may be permitted to exceed 100 degrees centigrade on occasion, without material effect upon the mechanical properties of overhead conductors, provided the temperature will seldom exceed, say, 130 degrees centigrade.

There are occasions, happily very infrequent in well-managed distribution-system operations, however, when the

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REFERENCE 2B

... conditions ... heavy loads with the failure of supply plant places the operator in a dilemma. His alternatives in such a circumstance are to mistreat certain surviving supply plants, to cut off certain customers, or to delay restoration of interrupted service. His choice naturally favors the customer, up to the point where the imminence of surviving plant failure seriously threatens inconvenience to other customers as well. The customer is pretty reasonable about a service interruption, so long as he knows that the interruption was unavoidable. If he were a metallurgist, however, he probably would be reluctant to agree that literal observance of a 130 degree centigrade line-conductor temperature limit was sufficient reason for a service interruption. He might have some reason to suspect that temperatures as high as 175 degrees centigrade to 200 degrees centigrade might be accepted for an hour or two without material impairment to the line conductor, because that is the range in which the annealing time is known to be in the order of days rather than weeks or years.

A test was made, therefore, to determine approximately what damage the conductor and its automatic line splices might sustain during operation for a few hours at 175 degrees centigrade to 200 degrees centigrade. The test was made in a 12-foot frame, in which four short sections of bare medium hard-drawn, number 00 stranded copper conductors and three automatic line splices were connected in series and stressed to a constant tension of 1,000 pounds—the approximate stringing tension. Thermocouples were placed on two sections of the conductors and in each of the line splices. A temperature of 200 degrees centigrade was maintained essentially constant at a control point on one section of the conductor for about eight hours a day on six successive days for an aggregate of 44 hours. During the test, the other section of conductor maintained an essentially constant temperature of 180 degrees centigrade. The line splices were about 20 degrees cooler than the conductors and gave no evidence of any change in their contact resistance.

After the temperature tests were completed, approximate (eight-inch extensometer) stress-strain tests were made on each of the test samples and also on an unheated sample of the original conductor from which the test samples had been cut. The unheated sample of number 00 conductor broke at 5,500 pounds tension after about 0.9 per cent elongation. The 180 degrees centigrade sample broke at 4,600 pounds tension after 1.7 per cent elongation, whereas the 200 degrees centigrade sample had 30 per cent elongation without breaking at 3,600 pounds tension. In each test, the strength of the splices was superior to that of the conductor.

Thus, it was concluded that the physical characteristics of the copper conductor and its automatic line splices would not be altered appreciably by short-time operations up to 175 degrees centigrade on rare occasio..., but that 200 degrees centigrade may cause serious annealing of the copper. The region between 175 degrees centigrade and 200 degrees centigrade appears to be a very critical one. Therefore, 175 degrees centigrade was accepted as the reasonable operating temperature ceiling for overhead copper conductors during the very rare emergencies in the life of a line when there might be a one- or two-hour coincidence of plant failure, maximum load, high ambient temperature, and low wind velocity.

The condition of the cover is a subordinate consideration. Hence the temperature of the cover, if present, should be correlated with the copper-temperature limits. Approximate calculations had indicated that 175 degrees centigrade copper would make about a 130 degrees centigrade maximum outside surface temperature for triple-braid weatherproof covering. This limit is severe but is still well below the 182 degrees centigrade (360 degrees Fahrenheit) minimum impregnating temperature recommended in the Purdue University *Engineering Bulletin* 43, November 1932. A drip test made on six standard samples of number 6 triple-braid weatherproof wire, oven-heated to 82 degrees centigrade for one hour, then to 130 degrees centigrade for two hours, developed bubbles on four

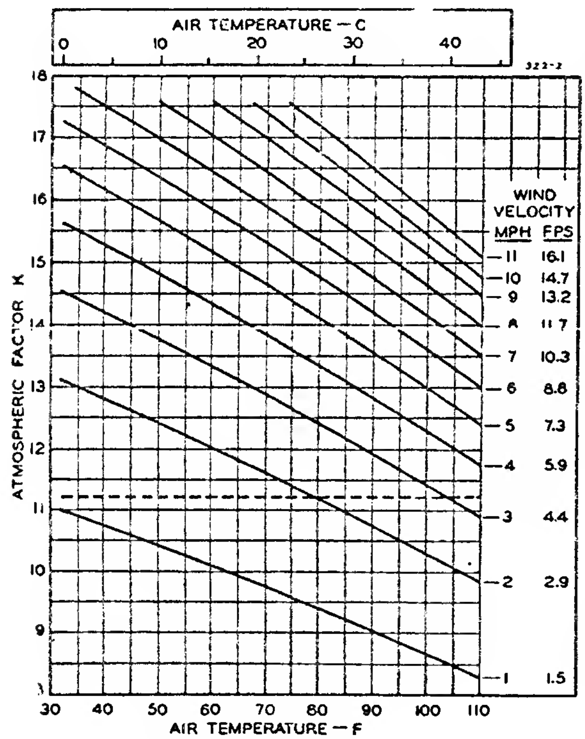


Figure 2 (left). Effect of air temperature and wind velocity upon atmospheric factor K

100 degrees centigrade surface—overhead

$K = \sqrt[4]{(t_s - A)^2 v}$

where

t_s = temperature of conductor surface—100 degrees centigrade

A = ambient temperature of air—degrees centigrade

v = wind velocity—feet per second

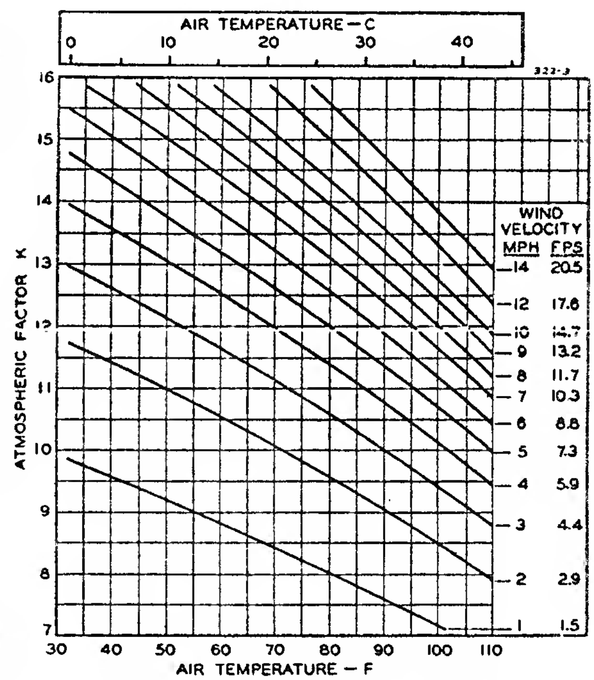


Figure 3 (right). Effect of air temperature and wind velocity upon atmospheric factor K

80 degrees centigrade surface—overhead

$K = \sqrt[4]{(t_s - A)^2 v}$

where

t_s = temperature of conductor surface—80 degrees centigrade

A = ambient temperature of air—degrees centigrade

v = wind velocity—feet per second

samples after the first half-hour at 130 degrees centigrade. Two samples showed no ill effects, and no compound dripped from any of the samples so tested. Time is a factor, hence the over-all effect of temperature and time is expected to be slight during a few nonconsecutive hours in the life of the cover, when there might be a rare coincidence of critical atmospheric conditions and emergency load. With 100 degrees centigrade copper, the outside-cover-surface temperature is estimated to be 80 degrees centigrade, or just

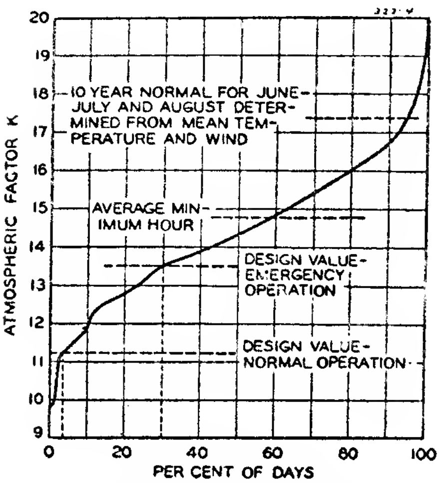


Figure 4. Minimum value of K in any hour for Philadelphia by days in June, July, and August, 1936–39

100 degrees centigrade surface

$K = \sqrt[4]{(t_s - A)^2 V}$

where

t_s = temperature of conductor surface—100 degrees centigrade

A = ambient temperature of air—degrees centigrade

V = wind velocity—feet per second

below the 82 degrees centigrade standard acceptance specification for triple-braid weatherproof wire. With the design limits of conductor temperature thus approximately determined, it becomes appropriate to review the effects of ampere loading upon temperature.

Conductor Heating

The conductor heating effects are three and need little elaboration. At a given ampere loading, the power losses increase as the conductor resistance increases with temperature. Part of the power losses is dissipated by radiation according to the Stefan and Boltzman law. The remainder of the losses in outdoor conductors is dissipated by forced convection, for which an approximate formula has been developed by Schurig and Frick,[1] who have also shown that the effect of sunshine becomes very small in heavily loaded conductors. The natural heat balance is quite simple. The complete algebraic expression for the relation between amperes load and temperature is somewhat unwieldy because of the dissimilarity between the separate effects that must be correlated. By the method detailed in the appendix, however, it will be seen that the principal effects of conductor diameter, conductor-surface temperature rise above ambient, and wind velocity, may be factored out so as to give the following convenient expression for ampere carrying capacity:

$$I = CKd\sqrt[4]{d+2s}$$

where d is the conductor diameter, s is the

Table I

		Normal Rating	Emergency Limit
Bare-Stranded Conductors			
Circular mils	500,000	1,090	1,350
	450,000	1,030	1,270
	400,000	950	1,160
	350,000	880	1,070
	300,000	800	970
	250,000	710	850
Number	0000	640	760
	000	550	650
	00	470	560
	0	410	480
	1	360	410
	2	300	350
Bare-Solid Conductors			
Number	0000	600	720
	000	520	620
	00	450	530
	0	390	460
	1	330	390
	2	290	340
Covered Conductors			
Number	0000	570	710
	000	500	620
	00	440	530
	0	380	460
	1	330	400
	2	280	340
	4	220	250
	6	160	180

cover thickness, K is the atmospheric factor, and C is a slow-moving residual coefficient which is essentially a constant for any given set of design limitations.

The principal effect of the conductor diameter and its cover, if present, may be seen in Figure 1, for the illustrative condition ($CK = 1{,}500$). The position of the curve for covered wire above that for bare wire, is not particularly significant. In Philadelphia, for instance, the apparent advantage of covered wire in Figure 1, is offset by an 11 per cent lower design limit of CK.

The atmospheric factor ($K = \sqrt[4]{(t_s - A)^2 v}$) may be evaluated directly from United States Weather Bureau data by the use of the chart in Figure 2 for bare conductors, or that of Figure 3 for covered ones, as the case may be. The results of such a survey may then be summarized, as in Figures 4 and 5. Maximum ambient temperature is not coincident with minimum wind velocity in the Philadelphia area. The 15-year maximum ambient of 40 degrees centigrade was accompanied by an 11-miles-per-hour wind. Other maximum ambients ranged from 35 degrees centigrade at five miles per hour to 39 degrees centigrade at 13 miles per hour. The most critical coincidence, 23

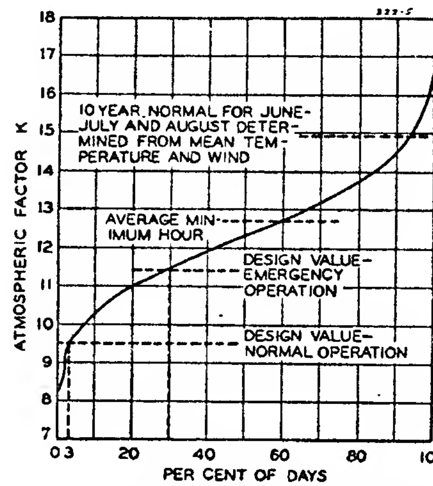


Figure 5. Minimum value of K in any hour for Philadelphia by days in June, July, and August, 1936–39

80 degrees centigrade surface

$K = \sqrt[4]{(t_s - A)^2 V}$

where

t_s = temperature of conductor surface—80 degrees centigrade

A = ambient temperature of air—degrees centigrade

V = wind velocity—feet per second

degrees centigrade at one mile per hour, made the lowest values of K shown in Figures 4 and 5. The condition did not persist for more than one clock hour in any day and occurred on less than six days in the average year.

It was considered reasonable therefore to permit copper temperatures to reach values in the neighborhood of 130 degrees centigrade with normal load or 175 degrees centigrade for any emergency load that might on a few rare occasions be coincident with so critical an atmospheric condition. The design values of K that are indicated in Figures 4 and 5 were selected so as to observe 130 degrees centigrade as the approximate ceiling for normal operations and 175 degrees centigrade as the ceiling for emergency operations. A summary of the resulting approximate maximum hour conductor temperatures during the three hottest months

of the year is given in Figure 6, which was developed by using arbitrarily the value of C that would give the maximum estimate of copper temperature.

As should be expected, the residual factor C does not vary through nearly the range of values that is characteristic of K. For normal design-limiting conditions in the Philadelphia area, the value is within 4.5 per cent of $C=126$ for bare-stranded, within three per cent of $C=142$ for bare solid, and within 5 per cent of

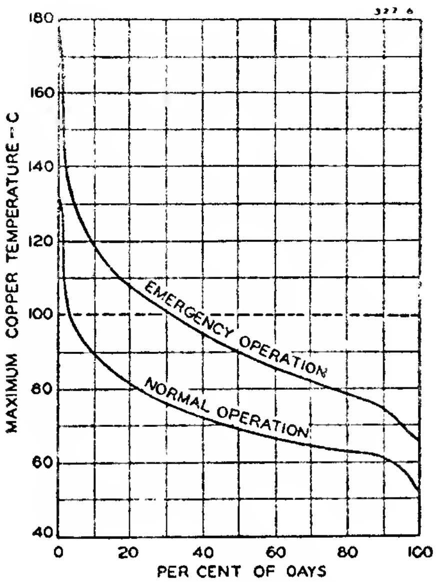


Figure 6. Approximate maximum-hour conductor temperature at ampere load limits in Philadelphia by days in June, July, and August

$C=148$ for covered conductors. For emergency operations in Philadelphia the most critical values occur in the smallest conductor size and are respectively: $C=119$ for bare-stranded, $C=135$ for bare-solid, and $C=144$ for covered wire.

Ampere Design Limits in Philadelphia

Table I summarizes the ampere design limits for overhead copper lines in Philadelphia, as developed by the method described in this paper.

Winter load limits will be somewhat higher than given in the table. Tentative indications are that normal ratings may be increased ten per cent and emergency limits five per cent from November through March. The limiting atmospheric conditions are not much less severe than in the warmer months. However, about one half of the winter hours with critical ambient-temperature–wind combinations are accompanied by rain.

Conclusions

1. The paper deals with the carrying capacity of conductors in overhead lines, as determined by the effect of temperature and time upon the physical characteristics of the conductor. The paper does not deal with considerations of voltage variation, power loss, nor other factors that may favor larger conductors than are physically adequate for the immediate purpose.

2. The common assumption that maximum ambient temperature and minimum wind velocity are coincident is not supported by a study of United States Weather Bureau records for the past 15 years in Philadelphia.

3. The ampere load limits for overhead conductors in any situation can be evaluated directly from local records of critical ambient temperature and wind by the method given in this paper. The cooling effect of rain is not included, because it is absent during otherwise critical hours in summer and during one half of such hours in winter.

4. Coincidence of load-limit amperes with an hour of critical atmospheric conditions seems to be a contingency so remote that the resulting copper-temperature ceiling need be observed only as required in order to avoid weakening or oversagging the conductor.

5. Conductor temperature ceilings of about 130 degrees centigrade normal and 175 degrees centigrade emergency maximum appear permissible if of short duration and sufficiently infrequent. A 44-hour test has indicated that a few hours at 175 degrees centigrade should not change materially the physical characteristics of medium-hard-drawn copper wire or of automatic line splices, but that 200 degrees centigrade might cause serious annealing of the wire.

6. To recognize for the present at least the need for caution in utilizing temperatures approaching a critical zone for copper wires, the ampere load limits for Philadelphia are designed to keep copper temperatures regularly below 100 degrees centigrade normal or 135 degrees centigrade emergency. During the past 15 years, however, there has been an average of six nonconsecutive hours per year when a coincidence of load-limit amperes with critical atmospheric condition might make the copper temperature in some part of the line approach a ceiling of about 130 degrees centigrade normal or 175 degrees centigrade emergency maximum.

Appendix. General Expression for Current Ratings of Overhead Conductors

The current-carrying capacity of medium-hard-drawn copper conductors in outdoor overhead service was calculated for steady-state conditions. In the steady-state condition, the heat dissipation is equal to the I^2R loss in the conductor, or

$$I^2R = WS \text{ watts} \tag{1}$$

where S is the surface area of the conductor; W is the sum of the watts radiated W_r and the watts dissipated by convection W_c, so that

$$W = W_r + W_c \text{ watts per square inch} \tag{2}$$

In surroundings of temperature T_o degrees Kelvin, the heat dissipation by radiation from long horizontal cylinders, with surface of E relative emissivity and surface temperature of T_s degrees Kelvin, is

$$W_r = \frac{36.8E}{10^{12}}(T_s^4 - T_o^4) \text{ watts per square inch} \tag{3}$$

The approximate formula of Schurig and Frick[1] for heat dissipated at sea level by forced convection in air moving v feet per second crosswise to horizontal cylinder with outside diameters $(d+2s)$ ranging from 0.3 to 5.0 inches is

$$W_c = \frac{0.0128}{T_a^{0.123}}\sqrt{\frac{v}{d+2s}}\,(T_s - T_o) \text{ watts per square inch} \tag{4}$$

where

$T_a = (T_s + T_o)/2$
d = copper diameter in inches
s = thickness of conductor cover in inches

Substituting equations 3 and 4 in equation 2

$$W = \frac{36.8E}{10^{12}}(T_s^4 - T_o^4) + \frac{0.0128}{T_a^{0.123}}\sqrt{\frac{v}{d+2s}} \times (T_s - T_o) \tag{5}$$

$$= (T_s - T_o)\left[\frac{36.8E}{10^{12}}(T_s + T_o)(T_s^2 + T_o^2) + \frac{0.0128}{T_a^{0.123}}\sqrt{\frac{v}{d+2s}}\right] \tag{6}$$

For convenience let

$$C_r = \frac{36.8E}{10^{12}}(T_s + T_o)(T_s^2 + T_o^2)$$

and

$$C_c = \frac{0.0128}{T_a^{0.123}}$$

then

$$W = (T_s - T_o)\left[C_r + C_c\sqrt{\frac{v}{d+2s}}\right] \text{ watts per square inch} \tag{7}$$

If it is assumed that about 75 per cent of the surface area of bare-stranded conductor is effective in heat dissipation, as is approximately true for radiation, then the effective surface area S of stranded copper is equal to that of a smooth cylindrical envelope and the heat dissipated per foot of conductor is

$$WS = 12\pi(d+2s)(T_s - T_o) \times \left[C_r + C_c\sqrt{\frac{v}{d+2s}}\right] \text{ watts} \tag{8}$$

The approximate average resistance per foot of medium-hard-drawn (97.5 per cent conductivity) copper of diameter d at T_c degrees Kelvin is

$$R = 10^{-6}T_c/26.7(\pi d)^2, \text{ or } 13.97 \text{ ohms per circular-mil foot at 100 degrees centigrade} \tag{9}$$

where r equals 1.00 for solid conductors, or approximately 0.87 for stranded conductor. Thus, from equations 1, 8, and 9

$$I^2=\frac{WS}{R}=\frac{320\pi(rd)^2(d+2s)\times 10^6}{T_c}(T_s-T_o)\times\left[C_r+C_c\sqrt{\frac{v}{d+2s}}\right] \quad (10)$$

$$I^2=\frac{320\pi r^2\times 10^6}{T_c}(T_s-T_o)d^2(d+2s)\times\sqrt{\frac{v}{d+2s}}\left[C_r\sqrt{\frac{d+2s}{v}}+C_c\right] \quad (11)$$

$$I^2=\frac{10^9 r^2}{T_c}\left[C_r\sqrt{\frac{d+2s}{v}}+C_c\right]\times\sqrt{(T_s-T_o)^2)v}\,[d^2\sqrt{d+2s}] \quad (12)$$

or

$$I=CKd\sqrt[4]{d+2s}\text{ amperes} \quad (13)$$

where

$$K=\sqrt[4]{(T_s-T_o)^2v}=\sqrt[4]{(t_s-A)^2v}$$

$$C=31{,}600r\sqrt{\frac{1}{T_c}\left[C_r\sqrt{\frac{d+2s}{v}}+C_c\right]}$$

$$=31{,}600r\sqrt{\frac{1}{T_c}\left[\frac{36.8E}{10^{12}}(T_s+T_o)(T_s^2+T_o^2)\times\sqrt{\frac{d+2s}{v}+\frac{0.0128}{T_a^{0.123}}}\right]}$$

A = ambient temperature in degrees centigrade
d = copper diameter in inches
E = relative emissivity of the surface
r = 1.00 for solid, or 0.87 for stranded conductor
s = cover thickness in inches
t_s = outside surface temperature in degrees centigrade
v = wind velocity in feet per second
T_o = ambient temperature in degrees Kelvin
$T_a=(T_o+T_s)/2$
T_c = copper temperature in degrees Kelvin
T_s = outside surface temperature in degrees Kelvin

Upon analyzing the factors in the expression for current, equation 13, it will be seen that:

K may be called an atmospheric factor and evaluated from Weather Bureau observations for any given design temperature t_s of conductor surface, as in Figure 2 for 100 degrees centigrade, or Figure 3 for 80 degrees centigrade.

C is a coefficient which compensates also for the residuals left after accounting for the major effects of d and K. C is practically a constant for all the usual overhead conductor sizes and combinations of high ambient temperatures with critically low wind velocities. For instance, all values of C lie within five per cent of 142 with the numbers 2 to 0000 sizes of oxidized (relative emissivity of 0.6) bare-solid conductors at temperatures from 100 to 175 degrees centigrade.

Reference

1. Heating and Carrying Capacity of Bare Conductors for Outdoor Service, O. R. Schurig, C. W. Frick. *General Electric Review*, volume 33, 1930, pages 141–57.

10B

Ampere Load Limits for Copper in Overhead Lines

Discussion and author's closure of paper 43-22 by A. H. Kidder and C. B. Woodward, presented at the AIEE national technical meeting New York, N. Y., January 25–29, 1943, and published in AIEE TRANSACTIONS, 1943, March section, pages 148–52.

Leonard M. Olmsted (Duquesne Light Company, Pittsburgh, Pa.): There can be no question of the timeliness of this paper. With every electrical power utility and industrial plant striving to carry greater and greater war loads with the minimum use of critical materials, there is great pressure upon them to utilize their present facilities to the maximum advantage. When this pressure is directed to overhead transmission lines, however, considerable caution must be observed lest the system be rendered unfit for continued use. Before ratings can be assigned safely to any line, at least eight factors must be considered carefully, namely:

1. The ability of the conductor to withstand the increased rating without excessive loss of mechanical strength by annealing.

2. The ability of connectors and joints on the conductor to withstand the increased rating without oxidation of the contact surfaces and local heating in excess of the allowable conductor temperature.

3. The adequacy of span clearances to permit the additional sag caused by the higher conductor temperature associated with the increased rating.

4. The problem of providing short-circuit and overload protection to operate within the decreased margin between the increased current rating and destructive overloads.

5. The adequacy of substation and terminal equipment to carry the increased currents for which the transmission conductors may be rated.

6. Operating problems of the bulk power system with individual circuits rerated to such high values that reserve line capacity no longer is available to replace capacity lost when such a line goes out of service.

7. The ability of voltage-regulating equipment to compensate for the greater voltage variations which accompany heavily loaded lines.

8. The considerable increase in energy losses arising from the greater line currents.

No engineer would contend that all eight are of equal importance, but neither could he afford to ignore any one until he had satisfied himself that it does not limit the particular line which he wishes to rerate.

With these aspects in mind, let us turn now to Kidder and Woodward's paper. There is no doubt that the extreme lack of elasticity and low tensile strength of soft—or annealed—copper wire render it unsuitable for transmission conductors. The cold-drawing process causes considerable increase in tensile strength and elasticity and permits design sags based upon storm-loading stresses up to 50 to 60 per cent of the ultimate tensile strength. Once designed for this cold-drawn tensile strength it is essential that the original tensile strength be preserved, as otherwise it becomes impossible to maintain safe ground clearances. This phase of the problem resolves itself into the seemingly simple solution of keeping the conductor temperature below the annealing point. A common figure for the annealing point of copper is 200 degrees centigrade, but further investigation of metallurgical literature discloses that considerable annealing of cold-drawn copper wire has been reported at temperatures as low as 80 degrees centigrade. Unfortunately, damage caused by a slightly excessive temperature may not be detected until long after the overheating occurred.

No extensive treatise upon the annealing of cold-drawn copper wire seems to be available, but metallurgists assure me that it should follow relationships similar to cold-rolled copper sheet which has considerably more literature. An extensive analysis of cold-rolled copper by N. B. Pilling and G. P. Halliwell[1] indicates the following:

1. For any given degree of cold-rolling, a curve showing the time for complete annealing at temperatures from 250 degrees centigrade down to as low as 100 degrees centigrade shows a logarithmic relationship, with the time at 100 degrees centigrade a matter of years.

2. The tensile strength has a definite relationship with the amount of cold working.

3. The greater the cold working (and tensile strength) the faster the rate of annealing.

4. While annealing time is expressed with complete annealing from hard-drawn to soft copper as 100 per cent, the first two per cent of that time removed nearly 50 per cent of the strength imparted by cold working. Thus, while the annealing time at 200 degrees centigrade may be "known to be in the order of days," considerable damage occurs at 200 degrees centigrade in a few hours.

From such tests as these, covering at most only a few months, we are forced to extrapolate to cover the 10, 20, or 50 years during which it is desired to use the conductors.

Assuming that these data apply exactly to cold-drawn copper wire, it would seem that the maximum temperatures of 130 degrees centigrade and 175 degrees centigrade used by Kidder and Woodward are definitely at the upper limit of what might be considered feasible. Certainly lower temperatures are indicated for the hard-drawn bare copper commonly used for transmission conductors.

With conductors loaded to the [illegible] where high currents are to be expected, it becomes vitally important that the lines be in absolutely perfect condition from terminal to terminal. Every joint and clamped connection must be perfect to avoid hot spots, and the common flashover burn where two or three strands may be parted would be almost certain to develop into a conductor failure during a subsequent sleet and wind storm. Since any line is likely to have some such defects after a few years of service, it would seem advisable to establish the current rating low enough to allow some margin to avoid subsequent failures caused by local hot spots.

Several types of connectors used in the original construction of lines 15 or 20 years ago have been found by inspection and laboratory test to be inadequate. In general the trouble was found to be warping of the contact surfaces and insufficient mechanical strength in the bolts, both of which seem to have been corrected in many of the connectors now on the market. Before conductor ratings can be increased, however, it is vitally necessary that all unsatisfactory joints and connectors be replaced. Even then there remains the probability that operation of the joints and connectors at temperatures in excess of 70 degrees centigrade will cause oxidation of the contact surface with subsequent excessive heating and damage to both conductors and connectors. While the mass and greater dissipating surface of the connector tend to hold the temperature somewhat below that of the conductor alone, it would seem to be good judgement to hold conductor temperatures below 100 degrees centigrade even for emergency loading.

Many transmission lines are designed for safe clearances at conductor temperatures on the order of 50 degrees centigrade. Raising the operating temperature to 100 degrees centigrade or more causes a considerable increase in length by expansion of the conductor and reduces clearances to ground by nearly four feet in a 1,000-foot span. Obviously, then, it is important to ascertain that the line has adequate clearances before the operating ratings are increased, and some lines may be limited by inadequate clearance.

Short-circuit and overload protection must be provided to function at current values above the rating and still below the level at which the conductors will be damaged. As the conductor operating ratings are pushed up, the margin remaining below the relay limit is correspondingly reduced, and adequate protection becomes a more difficult problem.

Terminal equipment in substations often is designed for a comparatively low current rating. While some equipment may be modified for increased ratings and other equipment replaced, it still is a vital part of any rerating program to ascertain that the terminal equipment involved is adequate to handle the increased rating which is proposed for the conductors.

One of the most difficult problems arising from high line ratings is that faced by the system operators who must endeavor to find ways to maintain uninterrupted service with the facilities remaining after one of the rerated circuits goes out of service. Not infrequently they will have to choose between overloading the remaining facilities

beyond . . . emergency ratings or dropping load, n . . her of which can be considered desirable.

For metropolitan areas such as Philadelphia, it is probable that transmission distances are short enough to eliminate voltage regulation and losses as limitations to transmission ratings. Most other utilities are not so fortunate, however, and may have lines limited by voltage drop and transient and static stability to ratings even below commonly accepted conductor ratings.

Undoubtedly Kidder and Woodward have considered all of the preceding problems in the analyses from which their paper was prepared. Undoubtedly also they intend their published ratings as absolute maximum values to be approached in practice but never exceeded. They have not taken full advantage of the probabilities found in the load characteristics, atmospheric temperatures, and wind velocities of the Philadelphia area. Even so, it would seem to be better judgement to set the ratings somewhat lower, at values where there is no danger of damaging the conductors. Other utilities would do well to conduct their own analyses of allowable conductor currents, incorporating the local atmospheric temperatures, wind velocities, and the load characteristics of the particular circuit in question. These analyses should allow for their own terminal-equipment limitations, types, and conditions of conductors, and operating problems, and probably will yield ratings materially lower than those published by Kidder and Woodward.

Reference

1. Softening of Hard-Rolled Electrolytic Copper, N. B. Pilling, G. P. Halliwell. *Proceedings*, American Society for Testing Materials, 1923, part 2, pages 97–119.

John G. Holm (Stone and Webster Engineering Corporation, Boston, Mass.): The authors' very interesting paper and its conclusions are of particular importance in connection with loading of overhead conductors in times of war emergency when power requirements are high and the lack of strategic materials acute.

One may not agree with the advisability of attaining what appears to be somewhat high copper temperature limits advocated by the authors; the fact remains, however, that conductors are being operated on the system of the Philadelphia Electric Company at the high temperatures indicated by the authors. If then a 500,000-circular-mil bare concentric stranded copper conductor may be operated normally at a current-carrying capacity of 1,090 amperes, the question suggests itself of what could be attained with hollow copper conductors under similar operating conditions.

For comparison an *HH*-type hollow conductor of the General Cable Corporation was selected. The current-carrying capacity of this conductor exceeds that of any other type of hollow conductors of the same copper cross section. Approximate, but fairly accurate calculations show that a 500,000-circular-mil *HH*-type conductor of the "normal minimum" design has a current-carrying capacity of 1,270 amperes under the same normal temperature conditions at which the concentric stranded conductor carries 1,090 amperes. At larger cross sections the difference in the current-carrying capacity of the two conductors increases, and at 1,000,000 circular mils it is about 22 per cent in favor of the *HH*-type conductor. This *HH*-type conductor, when operated at the normal temperatures given by the authors, has a current-carrying capacity more than 55 per cent larger than the 1,000,000-circular-mil stranded conductor designed to operate at standard conditions (50 degrees centigrade rise, 25 degrees centigrade ambient and wind velocity of two feet per second). If an *HH*-type conductor of the "undercut minimum" design had been selected for comparison, the percentage figures would be still higher.

If the temperatures suggested by the authors are safe, as indicated by their acceptance by the Philadelphia Company, then the great advantage of the *HH*-type conductor over the concentric stranded conductor would become immediately apparent, especially during the emergency operation. At the higher operating voltages, for which for obvious reasons the hollow conductor is especially suitable, the mechanical strength of the conductor requires a certain minimum copper cross section. If then, such a conductor is permitted to operate at temperatures advocated by the authors and is installed on a two-circuit line requiring the hollow conductor to carry the entire system load with a loss of one circuit or a section of it, its cross section must be increased toward the center, but comparatively little more than in the case where no such requirement is imposed on the conductor. When the line has three circuits, and the loss of one would mean an increase of 50 per cent for the normal load of the conductors, no increase in the normal cross-section design of the *HH*-type conductor would be required if temperatures given by the authors are allowed. This could never be attained with concentric stranded conductors.

Therefore, since during the present emergency it is important to have the copper carry all the current it safely can, it should be pointed out that copper may be made to go much farther as an overhead conductor when it is drawn in tubular form than when it is used in form of solid wires concentrically stranded.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): As might be expected from my publications on underground cable, I have been in favor of the principle of increased temperatures and ratings for overhead lines for some years. During the past several years new and higher ratings were established at various times for the system of the Commonwealth Edison Company.

The compounds in old-style coverings of weatherproof wire generally have softening points of 55 to 65 degrees centigrade, according to tests made at Purdue University about 1930 and tests made in Chicago subsequently. Accordingly, the temperature limits used in the special calculations for load ratings for such wire were 66 degrees centigrade for normal operation and 72 degrees centigrade for emergency operation. The corresponding limits for the URC type of covering were 77 and 88 degrees centigrade, respectively. Almost three fourths of our wire, however, had the older coverings and in most cases it was impracticable to determine which covering existed in a given circuit. That meant that in almost all cases the ratings used for the weatherproof wires were based on the temperatures of 66 and 72 degrees centigrade. With the advent of the war it was decided to allow rapid deterioration of the covering of the old-style weatherproof wires by using the same load ratings for them as for the URC type.

For our system the incentive to establish further increases in ratings is small because increased ratings would result in using smaller copper conductors in only five or ten per cent of the cases. In other words, regulation is more of a determining factor.

In 1936 we made some tests on URC-type wires with current applied continuously for six or for seven hours. The sizes were numbers 6, 0, and 4/0 and two or three tests were made on different samples of each size. The final copper temperatures were 85 to 157 degrees centigrade, and the conductors were practically at these temperatures for four or five hours.

Copper temperatures of 111 and 113 degrees centigrade on two different samples produced numerous pustules and some blisters in the coverings. In view of these facts for only one day's operation, and considering the data presented by the authors, it is not clear how the authors arrive at temperatures of 100 and 130 degrees centigrade for normal operation.

The Chicago tests with copper temperatures of 129 to 157 degrees centigrade for four or five hours on URC-type wire produced many blisters, the phenomenon being extreme and accompanied by practical destruction of the covering at 157 degrees centigrade. These data do not seem to justify emergency temperatures of 135 to 175 degrees centigrade, which are advocated by the authors. In general, the effects of the high temperatures obviously would be very much more severe on the weatherproof wires having the old-style coverings.

In setting up our ratings, one set was issued based on a summer ambient of 32 degrees centigrade and another set for midwinter based on an ambient of ten degrees centigrade. The former temperature merely takes into account the higher summer temperatures, while the use of the lower ambient in winter permits higher ratings in winter, which is of value in many installations. It is not clear from the article what the authors recommend on differentiating between summer and winter conditions.

The authors state that the effect of solar radiation is neglected. Using data of the United States Weather Bureau in Chicago, we find decreases of 5 to 15 per cent in ratings for summer conditions because of solar radiation and believe this factor should be taken into account.

Incidentally, the wind velocity assumed in our calculations is two feet per second, which is supposed to take into account the effect of the convection set up by the condition of having the weatherproof wire at a temperature considerably above the ambient. Also, it may be noted that the actual maximum temperatures in Chicago in summer and winter may be five or eight degrees centigrade above the values assumed for the calculations.

For bare wires, data given by H. P. Seelye and L. F. Hickernell at the meeting of the transmission and distribution committee of the Edison Electric Institute at Cincinnati last October indicate annealing of copper starting at 100 degrees centigrade. The amount of annealing increases rapidly with higher temperatures. One of these references shows about 40 per cent reduction in tensile strength of hard-drawn wire with just a few hours' operation at 175 degrees centigrade and correspondingly large increases in elongation. With the spacing of 14 or 18 inches between our wires, material increases in sag would result in short circuits between wires. From a private source we learn that annealing has been found in some cases starting at 85 degrees centigrade.

Another important point in connection with the use of higher temperatures is that the resistance losses are substantially increased all the way from the customer back through the entire system to the generating station. These increased losses in themselves may prove to be more of a disadvantage in regard to available reserve generating capacity than the gain in saving copper on new installations by using the extra-high copper temperatures on the wires.

It should be noted that an article like the authors' is unusual in challenging the thinking of engineers and thereby, in some cases, causing large benefits.

Earl H. Kendall (The Commonwealth and Southern Corporation, Jackson, Mich.): The authors are to be complimented on a very complete paper on a very timely subject. The following comments refer largely to the section entitled "Mechanical Limitations of Bare and Covered Copper."

The second paragraph of this section states that there is considerable uncertainty whether copper begins to anneal at 100 degrees centigrade or 130 degrees centigrade and that 100 degrees centigrade may be exceeded on occasion without effect on the mechanical properties of conductors. Considerable research has been conducted on the annealing of copper, and some of the data are presented in the American Society for Testing Materials symposium on the "Effect of Temperature on the Properties of Metals," June 1931. The data in the report indicate that the decrease in tensile strength is more rapid above 150 degrees centigrade, and from room temperature to 150 degrees centigrade the tensile strength decreases about ten per cent.

In the discussion of this report it is brought out that copper begins to anneal at 150 degrees centigrade and is completely annealed in about 96 hours. Also, it makes no difference whether the heating is continuous or intermittent so long as the total time elapsed at the temperature is the same. From this, it appears that for practical purposes the very limit for conductors should be somewhat less than 150 degrees centigrade.

The authors of this paper also say that 150 degrees centigrade to 200 degrees centigrade might be accepted for an hour or so without material impairment to the conductors. As 200 degrees centigrade is the recrystallization temperature for copper, and above this temperature copper deforms plastically under low stress, 200 degrees centigrade even for very short periods for wires in tension is very dangerous. In regard to the temperature tests on the sample conductors tested under tension, it is assumed that the tensile and the elongation tests were made on the complete conductor and not on the individual wires. Such tests are not conclusive because of errors introduced by such things as slippage, uneven elongation of the wires, stranding, and other such items. It would also seem that the sample tested at 200 degrees centigrade, which is the recrystallization temperature, was operated at too high a temperature to be of value. It would be of considerable interest to know how many tests were made and to know the length of the test samples as elongation and tensile strengths vary considerably even for new wire because of mechanical damage in handling, and so forth.

The paper accepts 175 degrees centigrade as a reasonable operating temperature ceiling for overhead conductors during the very rare emergencies when there might be one or two hours coincident of plant failure, maximum load, high ambient temperature, and low wind velocity. Such high temperature even for these rare cases will be very dangerous because this maximum temperature is based on conductors in good condition, which will not be the case of the ordinary overhead line over its entire length as there are always spots which have been damaged either mechanically or through electrical burns. Such spots when the conductors are operated at 175 degrees centigrade are, no doubt, above 200 degrees centigrade, which is the recrystallization temperature. It is indicated from other tests that much safer temperatures even for emergency use would be somewhere between 100 degrees centigrade and 125 degrees centigrade and certainly not greater than 150 degrees centigrade even for rare emergencies.

H. A. Enos (American Gas and Electric Service Corporation, New York, N. Y.): The authors of this paper have used the formulas presented by O. R. Schurig and C. W. Frick[1] in an article in the *General Electric Review* of March 1930, but state that they have rearranged these formulas to facilitate calculation. This has been done by regrouping the factors involved in the formulas so that one group can be set up as a constant called the atmospheric factor K and others grouped to provide another constant called the residual factor C. The authors have then evaluated these constants in terms of the climatic values derived from a study of weather bureau records in the Philadelphia area. A thorough examination of this method fails to disclose any considerable advantage to this method from the standpoint of calculation. On the contrary, it seems to introduce additional and quite unnecessary complication.

It is generally agreed that for the equilibrium condition the sum of the watts convected and the watts radiated minus the watts absorbed from radiation from the sun and adjacent objects is equal to the I^2R watts. For any given set of temperature and air-velocity conditions the watts dissipated by convection is equal to the ratio of the superficial area of the wire to the square root of its diameter, multiplied by an easily determined constant. Also, the net watts dissipated by radiation is given by an easily calculated constant multiplied by the superficial area of the wire. Furthermore, the watts absorbed in the form of solar radiation is equal to a simple constant multiplied by the diameter of the wire. Upon obtaining the value of the total net watts dissipated it is quite simple to determine the current which will provide those watts.

Because of the method the authors have used in presenting their data it is somewhat difficult to determine the actual values of some of the factors on which they have based their illustrative calculations. As near as can be determined in the case of covered conductors they have used a surface temperature of 80 degrees centigrade for normal operating conditions and a combination of wind velocity and ambient temperature which is quite indefinite as to the actual air-temperature values used. If, however, an air temperature of 40 degrees centigrade is assumed, the corresponding wind velocity indicated by their curves would be 3.5 miles per hour. In the case of bare conductors the surface temperature has apparently been assumed at 100 degrees centigrade for normal operation, and for 40 degrees centigrade ambient the corresponding wind velocity would be three miles per hour. It is difficult to understand the discrepancy between the wind-velocity values for bare and weatherproof conductors. I find nothing in the paper to indicate what conductor surface temperatures were actually used in calculating carrying capacities for emergency operation. The paper hints that these temperatures are about 130 degrees centigrade.

The authors justify their use of relatively high wind velocities because the weather bureau records for several years in the Philadelphia area indicate that in less than three per cent of the days during June, July, and August, would there be temperature and wind-velocity values more unfavorable than the ones selected. This conclusion may have serious results if it is relied upon either by the authors or others, because weather statistics covering only a few years are no guarantee that a worse combination of temperature and wind velocity might not appear at any time and last for a sufficiently long period to endanger the conductors and to reduce seriously clearances. This is all the more dangerous because the authors have assumed that the direction of wind movement is always at right angles to the conductors. As a matter of fact, there is no reason why it could not be parallel to the conductors, in which case the dissipation because of convection would be reduced enormously. The fact that a worse combination of air movement and temperature is possible is shown by the tests made by Schurig and Frick in which low wind velocities combined with high temperatures existed several times for several hours at a time.

The authors have accepted the erroneous conclusion arrived at by Schurig and Frick that the effect of solar radiation is negligible. It is true that it is relatively small in the case of bare conductors, but it is quite large in the case of covered conductors. Furthermore, it is so easily calculated that there seems to be no good reason for ignoring it.

Schurig and Frick presented a formula for the calculation of the heat dissipation by radiation. This formula which is quite accurate for inside conductors where the temperature of the walls of the enclosure is the same as the temperature of the air, but it is not, as Schurig and Frick assumed, correct for overhead conductors outdoors. Unfortunately, the authors of this paper have fallen into the same error as did Schurig and Frick. The correct formula for outdoor conductors suspended in the open above the earth contains as an effective emissivity factor a factor equal to the product of the respective emissivities of the wire and the surroundings. Schurig and Frick's formula contains a similar factor equal to the emissivity of the wire only. The correct formula also contains an additional factor known as the angle factor which is a function of the solid angle through which both the wire and the surroundings "see" each other. One component of the radiation formula involves only the net interchange of heat between the earth and the wire. Other factors must be introduced which evaluate the radiation from the wire to the open sky. Under certain conditions the radiation to other surrounding objects should also be included. The effect of using the incorrect formula for radiation results in a reduction of about 50 per cent in the actual amount of heat dissipated by radiation.

Schurig and Frick based their conclusion that the effect of solar radiation was negligible on the results obtained from tests conducted on bare conductors. However, a close examination of their test data will bring out the fact that the tests they used to make such a comparison were made at different times and under different conditions and, therefore, have only partial validity. Since no tests were made on weatherproof wires, a conclusion that solar radiation has negligible effect upon the temperature rise or the current-carrying capacity of weatherproof wires is far from justified. The contrary is confirmed by the results of calculations which show that in the case of number 4/0 weatherproof wire the solar radiation reduces the current-carrying capacity about 55 amperes, or over ten per cent on a clear summer day. In the case of number 6 wire it reduces the carrying capacity about 11 amperes, or about eight per cent.

Calculation of current-carrying capacities of weatherproof wires by the correct formulas indicates that adequate current-carrying capacities are possible to meet any reasonable needs for additional current-carrying capacity under wartime conditions, over and above what has been considered good practice in the past, without increasing temperature limits to values which are on the verge of endangering the strength of conductors. Adequate current-carrying capacities are also possible without the necessity of assuming wind velocities which are greatly in excess of those which can be reasonably expected to occur sometime combined with high ambient temperatures and which can last for a sufficient length of time to cause unexpected excessive temperature rises. On distribution systems even the range of voltage variation which is considered satisfactory under wartime conditions, and which is more than double the usual range, will be reached and passed long before the current-carrying capacity values determined on the basis of the authors' methods will have been reached. Therefore, there seems to be little excuse for stretching current-carrying capacities until they closely approach the ultimate limit. Furthermore, it should be remembered that the resulting excessive wire temperatures will cause such excessive sags that there will be presented an almost insurmountable problem in constructing and maintaining overhead circuits. This whole problem of current-carrying capacities needs to be studied with a proper and rational consideration of all the factors involved. Adequate tests should be made also to check the accuracy of the methods of calculation adapted.

Reference

1. Heating and Carrying Capacity of Bare Conductors for Outdoor Service. O. R. Schurig, C. W. Frick. *General Electric Review*, volume 33, March 1930, pages 141–57.

A. H. Kidder: The authors are indebted to the discussers of their paper for their emphasis of points that may need some clarification. The need for caution in utilizing temperatures approaching a critical zone for copper is one of which the authors were very conscious in the development of ampere load limits for their situation. Differences of opinion are to be expected and have to be reconciled in each particular situation. The opinions given by the discussers are very similar to many that were weighed in developing ampere load limits for Philadelphia.

The authors have undertaken only to present a method by which the probable effects of ambient temperature and wind velocity upon ampere load limits for overhead conductors may be accounted for confidently by straightforward recognition of *coincident* wind and ambient temperature observations. In the situation which the authors have used to illustrate their method the mean ambient temperature was 24 degrees centigrade and the mean wind velocity was 11 miles per hour during the three hottest months of the year. The authors' analysis of the coincidences, summarized in their evaluation of the atmospheric factor K, has developed that the average minimum hour value of K occurs at 31 degrees centigrade and seven miles per hour; the design value for emergency operations occurs at 33 degrees centigrade and five miles per hour; the design value for normal operations occurs at 27 degrees centigrade and two miles per hour; while the absolute minimum values of K occurred only at 23 degrees centigrade and one mile per hour. Under average atmospheric conditions during the three hottest months, therefore, there will be over five times the wind velocity needed to keep the conductor temperature below 100 degrees centigrade at normal load rating or below 135 degrees centigrade at the emergency load limits in Philadelphia. Extension of their survey to include the past 15 years of weather observations has not disclosed any coincidence more severe than 23 degrees centigrade at one mile per hour.

The authors have recognized frankly that temperature ceilings might be reached under certain very improbable coincidences of load and limiting atmospheric conditions. The temperature ceilings could not be bona fide limits if they were not severe. The authors have emphasized the need to provide adequate clearance wherever there is a possibility that such ceiling temperatures might be reached. The integrity of a paper on ampere load limits would be questionable, if operations under the severest possible conditions could affect neither the cover of the wire nor the crystal structure of the copper. The product of the probability of load equal to the load limit of the conductor[1] by the probability that the most critical atmospheric conditions will obtain in those hours of load-limit loading indicates a contingency so remote in normal distribution operations and so very, very remote in emergency distribution operations that it will be a very rare occasion indeed when copper temperatures above 100 degrees centigrade are to be expected in the conductors of a circuit designed to observe the load limits in Philadelphia. In fact, the average maximum hour copper temperature to be expected during the three hottest months in Philadelphia is 85 degrees centigrade if operating at the emergency load limits, or 70 degrees centigrade if operating at the normal design limits, but only 39 degrees centigrade for the average circuit in which there is better than a four to one chance that the load will be below 60 per cent of the normal design limit. The authors, therefore, do not consider themselves to be advocates of high temperature operations.

Most readers of the paper will observe that it deals exclusively with the physical characteristics of the conductor as distinguished from other limitations which can become critical in certain cases before the ampere load limits of the conductor are reached. Points not already covered in this more general discussion will be reviewed now in the order in which they were raised by the discussers.

Mr. Halperin's evident concern about the cover of the wire is definitely a secondary consideration. Taking reasonable precaution against premature inadequacy of conductor sizes used for new installations will in all ordinary circumstances provide sizes which will operate for years well within Mr. Halperin's temperature limits. The value of load limit operations will be determined by the extent to which they will postpone retirements of conductors whose true adequacy is considerably greater than would be indicated by calculations based upon hitherto conventional assumptions. The authors consider the probability of somewhat accelerating deterioration in the cover on such occasions, to be definitely secondary to the alternative of preserving the cover by retiring the installation.

Review of solar radiation shows it to be much less of a factor than Halperin and Enos expect. "A Summary of Total Solar and Sky Radiation Measurements in the United States," by I. F. Hand[2] gives the maximum mean hourly total of radiation on a horizontal surface to be 65.6 gram-calories per square centimeter in Washington, D. C., 64.0 in New York City, and 57.7 in Chicago. The higher figure corresponds to 0.49 watt per square inch received on the (DL) square inches horizontal projected surface of the conductor and dissipated from the $(\pi\ DL)$ square inches of conductor surface. This would make from 1.8 per cent to 2.2 per cent reduction in the

load limits calculated for bare wire by the author's method, or 2.3 to 2.9 per cent for covered wire. The load limits quoted in the paper, however, were so conservatively calculated that they are understated by a margin sufficient to absorb solar radiation without reaching the stated temperature ceilings.

Mr. Halperin quotes some opinions about annealing of copper wire. Conflicting hypotheses and opinions will make some controversy until more direct evidence has been accumulated. In the meantime, however, the authors have the assurance of knowing that the medium hard wire they tested lost 16.5 per cent of its initial strength in 44 hours at 180 degrees centigrade, an average loss of four-tenths per cent per hour. As in the case of the cover, the eventual cost of accelerating somewhat the present rate of deterioration in the strength of a conductor is preferred to the heavy expense of an immediate replacement. When one considers the improbability of temperatures approaching 100 degrees centigrade, it seems almost certain that the wire will have been retired for some other cause long before its strength shall have deteriorated by as much as 15 per cent. Some allowance for decreasing tensile strength may be made quite simply if and when desired, by some reduction in stringing tensions.

Mr. Enos' observation that the authors' method introduces some extra work in the calculations of wire rating is pertinent. The authors were willing to do the extra work in order to make their calculations recognize the probable *coincidences* of wind and ambient temperatures in which the conductors will operate. Their calculations include a 15-year survey of limiting atmospheric conditions. The authors discarded consideration of parallel versus crosswise wind, as soon as they realized that conductor sag and the natural turbulence of the wind would make the cooling effect much more nearly independent of apparent wind direction than would be developed from calculations based upon the arbitrary assumption of laminar air flow in the plane of an absolutely horizontal conductor. The vertical components of the natural air motion outdoors will be "crosswise" at all times.

Mr. Enos should have had no trouble recognizing the surface temperatures, because they are given in the titles of the Figures 2, 3, 4, and 5 to which he refers in the paper. Figures 4 and 5 summarize actual coincidences of ambient and wind with two different surface temperatures. Hence, the design value developed by the survey of Figure 4, for a 100 degree centigrade surface, should not be expected to occur at the same wind velocity as that developed from the survey of Figure 5, for an 80 degree centigrade surface. The authors would not have expected a better correlation than Mr. Enos found in his comparison between Figures 4 and 5 at 40 degree centigrade ambient. The calculations for emergency operation are based upon a 175 degree centigrade surface temperature ceiling for bare conductors and upon a 130 degree centigrade surface temperature ceiling for covered wire.

Mr. Enos alleges that Schurig and Frick have made a serious error because they did not, in their formula for radiation, separately identify either the "angle-factor," or the "emissivity factor" of the inclosure surrounding the conductor. For the case of a completely inclosed body which is small compared with the inclosing body, as in the case of a conductor suspended outdoors, Mr. Enos will find upon further investigation that the angle factor is unity and that the emissivity factor of the enclosure also is unity. Schurig and Frick have overlooked neither factor. The over-all accuracy of their formulas has been corroborated in the tests which the authors have made.

Mr. Kendall assumes correctly that the authors' tests were made on the complete conductor rather than on its components. The samples were over four feet long in each case. Tensile tests included both the wire and the associated automatic line splices at the ends of each sample, as left undisturbed in their places throughout both the electrical and mechanical tests. Three eight-inch extensometer measurements were made on each sample, one between benchmarks on the conductor, a second between a benchmark on the conductor and a benchmark on the adjacent splice sleeve at one end of the test sample, and the third, like the second, made between the wire and the splice sleeve at the other end of the test sample. The authors had expected some trouble with strand slippage, and so forth, but the extensometer tests from wire to splice disclosed no evidence of it. The lay of the strands had been pretty well compacted during the heat runs under tension in the test frame. The samples were moved from the electrical to the tensile test, without bending. The authors, therefore, have confidence in their test but realize the limitations of the eight-inch extensometer. The tests were made primarily to determine breaking strength.

The authors do not share Mr. Kendall's concern about the limiting effect of spots where there have been electrical burns or mechanical damage. They are satisfied that the copper has long since been completely annealed at the location of every burn which has any significant effect upon the conductor cross section. Mechanical failure is to be expected at mechanical weak spots. It is to be expected long before there would be any reasonable probability of further weakening by operations in Philadelphia of circuits designed to observe the stated ampere load limits.

Mr. Holm appropriately calls attention to the substantially higher ampere load limits which can be secured when desired by taking advantage of the greater surface to cross-section ratios that are obtainable in tubular conductor shapes or their equivalents.

Mr. Olmstead's review summarizes very well both the paper and the discussion of it. Each of the factors he lists is one to be considered in establishing line ratings, although the last five factors lie beyond the stated scope of the paper at hand.

References

1. Notes on Emergency Ratings, A. H. Kidder. AIEE Transactions, volume 58, 1939, November section, pages 602–3, Figures 2b and 3.

2. A Summary of Total Solar and Sky Radiation Measurements in the United States, I. F. Hand. *Monthly Weather Review*, volume 69, April 1941, pages 95–125.

TABLE OF CONTENTS

REFERENCE 3B

220 KV
LINE AND TERMINAL EQUIPMENT THERMAL CAPABILITY STUDY
ELECTRICAL RESEARCH PROJECT T-44

Introduction

In order to make maximum use of our present transmission and substation facilities, as well as to develop realistic line and station specifications for future additions to the system, it is necessary to determine a thermal capability for the 795 and 1033.5 Mcm line conductors and the substation terminal equipment. Some work has already been done along these lines (for example, the thermal rating of self-cooled oil-filled transformers) and the subject study expands this work to include thermal capabilities for major substation terminal equipment as well as the transmission lines between substations. These thermal ratings apply specifically to our system conditions, and take into account the small probability of simultaneous occurrence of limiting conditions, such as high temperature, low wind velocity, and maximum circuit loading.

Conclusions

1. With few exceptions, the maximum conductor temperature of the 220 kv transmission lines is limited by the increased conductor sag when operating at higher temperatures. This increased sag reduces the conductor ground clearance and clearance over facilities of foreign utilities.

2. The maximum current for the line conductors must be limited to a value which will produce a conductor temperature no greater than that allowed by minimum clearance requirements.

3. From a thermal standpoint, terminal equipment in 220 kv substations is as good as, or better than, the connecting transmission conductors, with the exception of several 800 ampere line traps which must be tested to determine their overload ability. However, in order to operate at the higher

temperature levels, all connectors, terminals, air break switch and OCB contacts must be properly maintained in order to insure that contact area will not overheat.

4. The attached Summary (Appendix I) shows the existing maximum operating current under summer and winter conditions for the 795 and 1033.5 Mcm line conductors. Also noted are limitations imposed by sub-station terminal equipment.

5. The capacity of most lines can be increased by making certain construction changes on the line. The ultimate capability under summer and winter conditions for each line is also shown on the attached Summary (Appendix I), along with the additional limitations imposed by terminal equipment.

6. These maximum currents, with the load durations typical of our system and weather conditions typical of our area, will result in negligible conductor annealing.

Further details as to the changes needed to increase the capability of specific lines are given in Appendix II.

Cost estimates to remove both the existing and ultimate terminal equipment limitations are given in Appendix III.

Results of tests to determine overload capability of line traps will be given in a supplementary report.

Summary

By taking advantage of the thermal capability of 220 kv lines and substation terminal equipment as determined in this report, 220 kv lines can carry currents one and one half times those presently specified in conductor hand books.

The operating temperature for 6 out of the 13 existing 220 kv lines on PP&L Co. system is limited to 49 C (120 F) due to the ground clearances which were specified in former design conditions. This limits the current to 775 amperes in the summertime and 1050 amperes in the wintertime for 795 Mcm ACSR conductor.

Construction changes as specified in Appendix II are necessary to take full advantage of the thermal capability of these six 220 kv lines.

Construction changes as specified in Appendix III are necessary to take full advantage of the thermal capability of the terminal facilities.

P.H.

C.H.S.

APPROVED:

B. Van Ness Jr. / CHS
Chief Electrical Engineer

7/6/60
E.E.Dept.
E.F.Reis:V.S

WRSa

DISCUSSION

General

At the outset, it must be noted that this study was conducted strictly on a thermal basis; no consideration has been given to limitations imposed by voltage drops, system stability, etc.

The first step in the study is to determine capabilities for the most commonly used transmission line conductor sizes, both copper and ACSR, starting with the 220 kv system. This will specify the maximum current which can be transmitted between stations as limited by the conductor, and it will be necessary to investigate only those terminal facilities whose published rating is less than this maximum line current.

Procedure

Two methods can be used to solve this particular problem:

1. Determine the maximum conductor operating temperature for each line, giving proper evaluation to allowable loss of strength, minimum clearances and conductor limitations. From this, the current carrying capacity can be determined from curves or formulas, taking into account the probability of simultaneous occurrence of high ambient temperatures, low wind velocity and time of maximum loading.

2. Determine from system conditions the maximum current which each line will be required to carry. From this and the known ambient temperature and wind velocity, the maximum conductor temperature can be calculated. Check each line at this temperature for satisfactory clearance and cumulative loss of strength.

Method #1 is used throughout this study. Method #2 would require continually revising the conductor limitations as system conditions changed.

Characteristics of Copper, Aluminum and ACSR Conductors

Two factors must be considered when a copper or aluminum conductor is operated at temperatures above the normally used design temperature:

1. Increased sag resulting from thermal expansion may reduce conductor clearances below minimum safety requirements.

2. Heating causes a loss of conductor tensile strength (annealing). This is a cumulative condition and subsequent ice loadings on a partially or fully annealed conductor under tension could result in increased sags with corresponding reduction in clearance and/or failure of the conductor.

Meetings were held with representatives of Alcoa Aluminum and Anaconda Wire & Cable Corp. to discuss the characteristics of aluminum and copper conductors. Because of the many variables involved in line construction, conductor size, minimum clearances and allowable loss of strength, neither company would make recommendations concerning the maximum operating temperature for transmission line conductors. However, they presented various curves which show the relationship between loss of tensile strength, operating temperature and time for conductor grade aluminum and copper. Figure 1 shows that for an aluminum conductor, annealing begins at a temperature slightly above room temperature but that the rate of annealing is not significant until aluminum exceeds 85 C (185 F).

On the other hand, the strength of the steel core in ACSR conductor remains essentially constant up to 450 C (842 F). Therefore, the annealing curves for ACSR conductor are a composite of annealing curves for steel and for aluminum, the exact relationship depending on the ratio of aluminum to steel strands in the ACSR cable. Calculations show that for 795 Mcm, 54/7 ACSR conductor, a 20% loss of strength in the aluminum strands results in an 11% loss of strength in the complete cable.

TYPICAL THERMAL-TIME CHARACTERISTICS
OF AN ALUMINUM CONDUCTOR

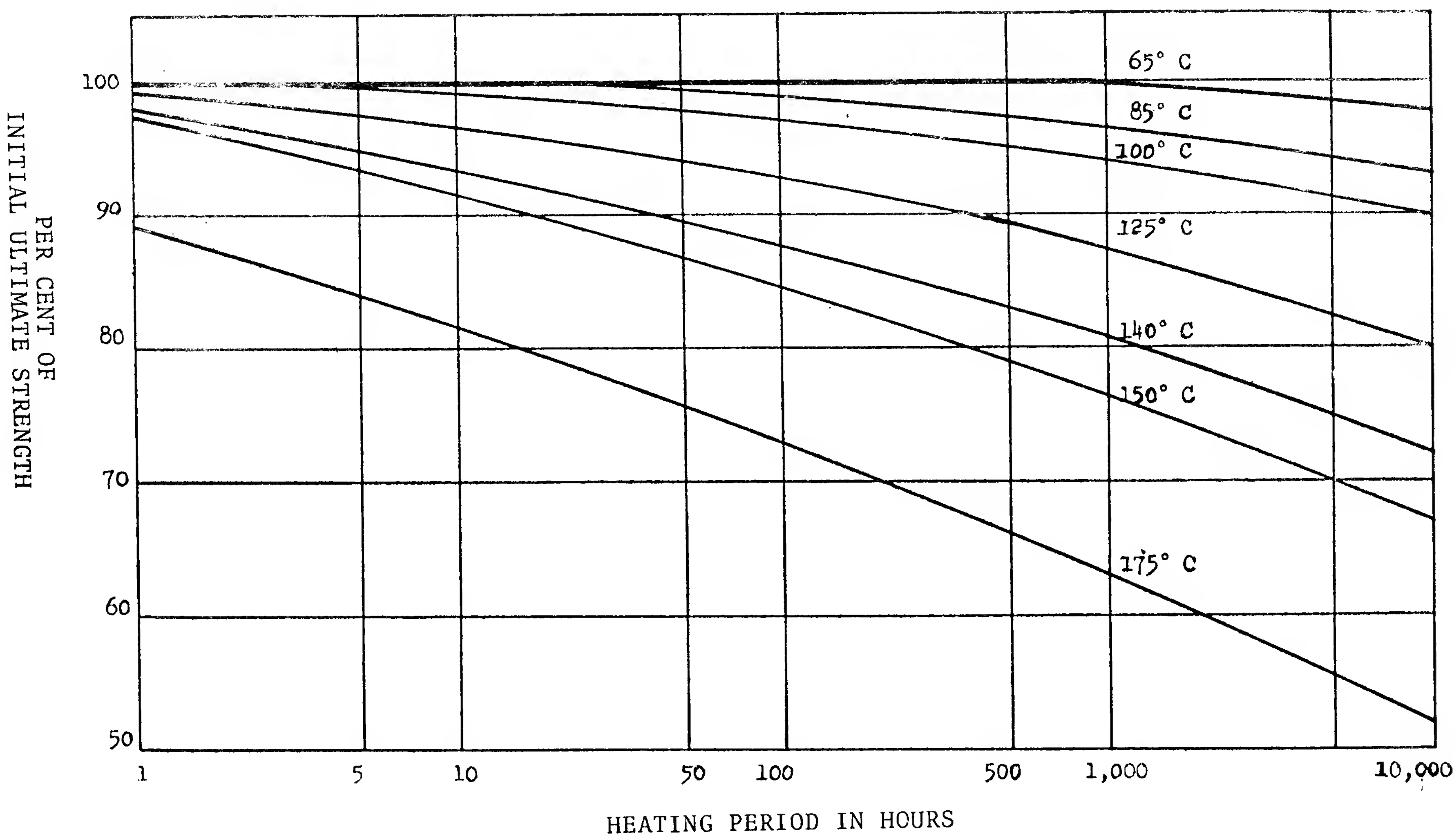


Figure 1

TYPICAL THERMAL-TIME CHARACTERISTICS
OF A COPPER CONDUCTOR

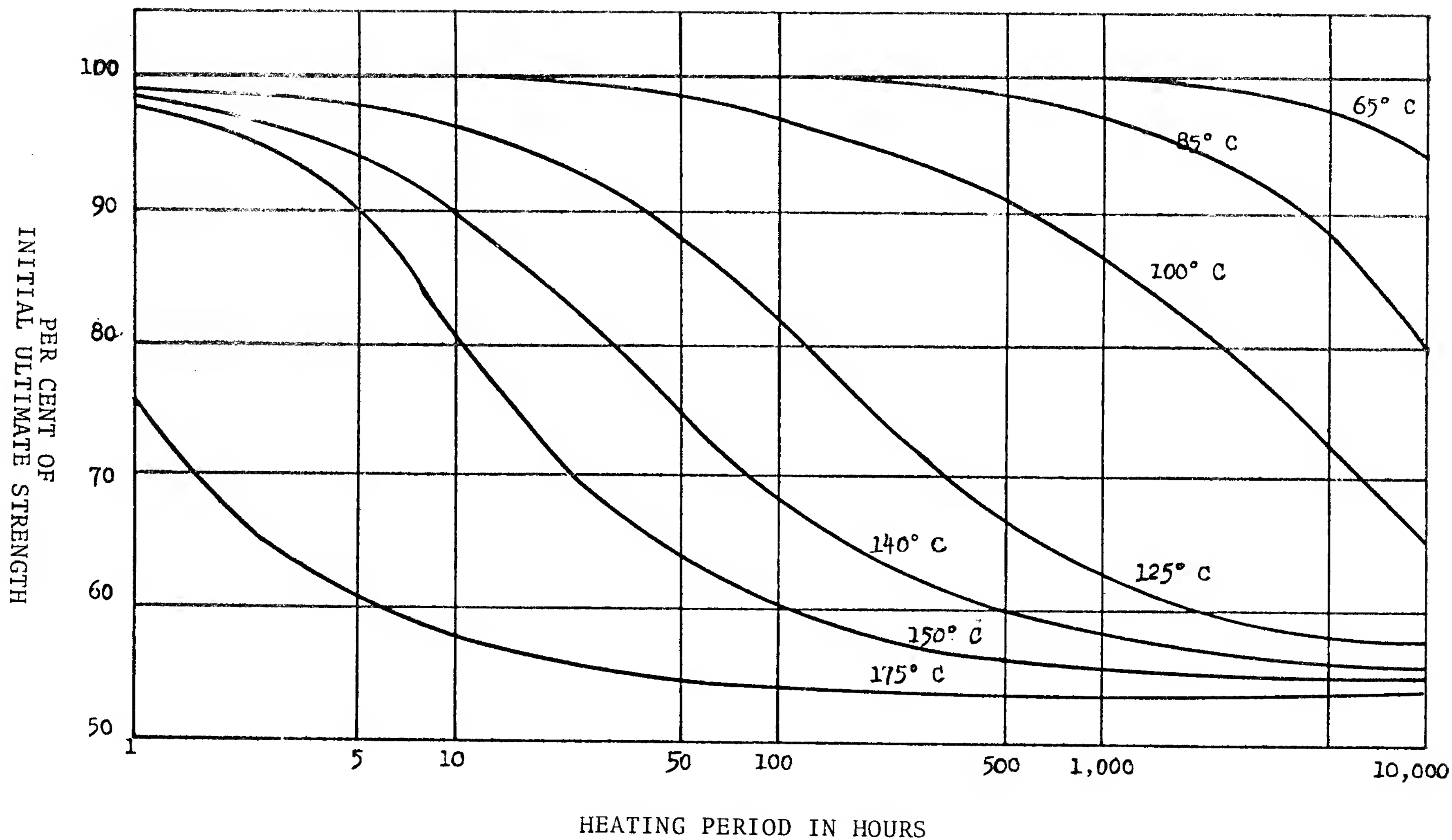


Figure 2 shows typical annealing curves for a copper conductor and indicates that the conductor can be operated continuously at 60 C (140 F) with essentially no allealing. Operating at 85 C (185 F) produces 3% loss of strength in 1000 hours and 20% loss of strength in 10,000 hours. The annealing associated with high temperature operation in both aluminum and copper conductors is cumulative.

Any closed magnetic circuit around the conductor, such as that made by malleable iron suspension clamps on older lines, could result in a temperature at the clamp higher than the conductor temperature at mid-span, depending on the ratio of heat producing ability of the clamp to its larger heat dissipating area. Higher temperatures are particularly liable to occur if magnetic type clamps have been installed without armor rods.

For conductors which are not under mechanical stress, annealing need not be considered, and the operating temperature is limited by the connectors, the clearance to other conductors, or the melting point of the conductor.

Collection and Processing of Weather Bureau Data

In 1943, a paper entitled "Ampere Load Limits for Copper in Overhead Lines" was presented to the AIEE by Messrs. A. H. Kidder and C. B. Woodward, both of the Philadelphia Electric Co. This paper proposed line limitations based on a study of U.S. Weather Bureau data to determine the probability of simultaneous occurrence of high temperatures and low wind velocities. By combining certain terms in the original Schurig and Frick formulas*, a so-called weather factor can be derived. A literature search revealed that there are several other formulas from which a similar weather factor can be obtained. One of these was unduly complicated, taking into account such variables as absolute viscosity, density, and thermal conductivity of air, while other formulas made too many unwarranted simplifying assumptions.

Formula for Current Carrying Capacity

The expression finally decided upon for our study is adapted from an article appearing in the Electrical World, May 15, 1943, entitled "Current Carrying Capacity of Overhead Conductors" by Mr. H. A. Enos. Reduced to its simplest terms, this relationship is:

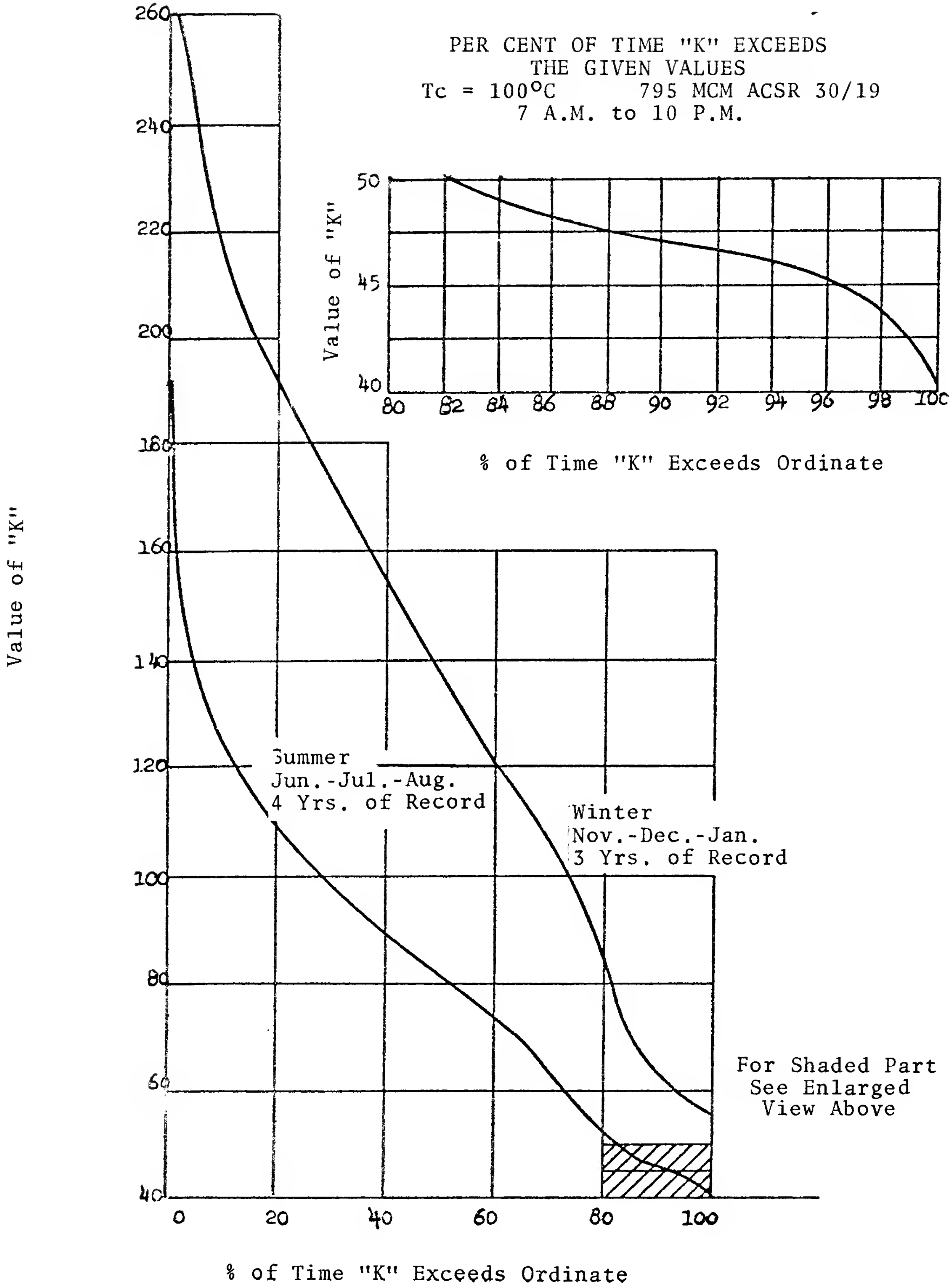
$$I^2R = \frac{(1.7 \times 10^{-4})\ (T_c - T_a)\ (T_c + T_a)^{.754}}{\log\left(\dfrac{.000305\ (T_c + T_a)}{(VD)^{.57}} + 1\right)} = K$$

where I = current in amperes, R = conductor resistance in ohms per foot, T_c = conductor temperature in absolute degrees, T_a = ambient temperature in absolute degrees, V = wind velocity in feet per second and D = conductor diameter in inches.

K can be evaluated from Weather Bureau data for any given conductor and surface temperature (T_c)

* Bibliography Item 1.

The next step was to gather all available hourly Weather Bureau data for the PP&L system. For the summer months (June, July and August) four years of records were available, three from Allentown-Bethlehem-Easton Airport and one from Harrisburg Airport. For the winter months (November, December and January) three years of records were available from Allentown-Bethlehem-Easton Airport. This information was transferred to punched cards and processed on the IBM 650 computer, which combined the various ambient temperatures and wind velocities with an assumed conductor temperature of 100 C to calculate a frequency distribution curve of the weather factor, K, for 795 Mcm ACSR conductor. This distribution curve for both summer and winter months is shown in Fig. 3.



PER CENT OF TIME "K" EXCEEDS
THE GIVEN VALUES
Tc = 100°C 795 MCM ACSR 30/19
7 A.M. to 10 P.M.
Value of "K"
50
45
40
80 82 84 86 88 90 92 94 96 98 100
% of Time "K" Exceeds Ordinate
Value of "K"
260
240
220
200
180
160
140
120
100
80
60
40
Summer
Jun.-Jul.-Aug.
4 Yrs. of Record
Winter
Nov.-Dec.-Jan.
3 Yrs. of Record
For Shaded Part
See Enlarged
View Above
0 20 40 60 80 100
% of Time "K" Exceeds Ordinate

Taking the summer curve as an example, it is seen that the lowest value of K is 40 and this would be the limiting factor as far as summertime maximum current carrying capability is concerned. The lowest winter value of K is 55. Since the conductor diameter appears in the denominator of the logarithm of the expression for K, the values of K would change very little for other size conductors.

Calculation of Current Loading

Determination of Conductor Temperature

After determining the frequency distribution of weather, a program was set up on the IBM 650 computer whereby the maximum conductor temperature corresponding to certain currents can be calculated for various size conductors, both ACSR and copper. Essentially, the steps involved are as follows:

1. The wind velocity is assumed constant at 2 ft per second. From the previously calculated values of K and a conductor temperature of 100 C, a corresponding ambient temperature is determined for specific values of K between 40 and 60, since it is these lower values which impose the temperature limitations on a conductor.

K	T_a
[illegible]	[illegible]
[illegible]	-0.5
50	[illegible]
55	[illegible]
60	[illegible]

2. This calculated ambient temperature, along with a wind velocity of 2 ft per second, is substituted for a specific conductor whose resistance and diameter are known.

3. The corresponding conductor temperature for different values of current is calculated from the above formula. Current is varied in 100 amp steps, and the program ceases automatically when conductor temperature falls below 40 C (104 F). From this, a family of curves can be plotted showing the conductor temperature versus the maximum current for specific values of the weather factor K. A sample of these curves is shown in Figures 4 and 5, for 795 Mcm ACSR conductor and 1033.5 Mcm ACSR conductor, respectively. Figure 4 shows that for K = 40 (minimum summertime value), 795 Mcm ACSR conductor can carry 1300 amps without exceeding 125 C conductor temperature. Figure 5 shows that a 1033.5 Mcm conductor can carry 1500 amps under similar conditions.

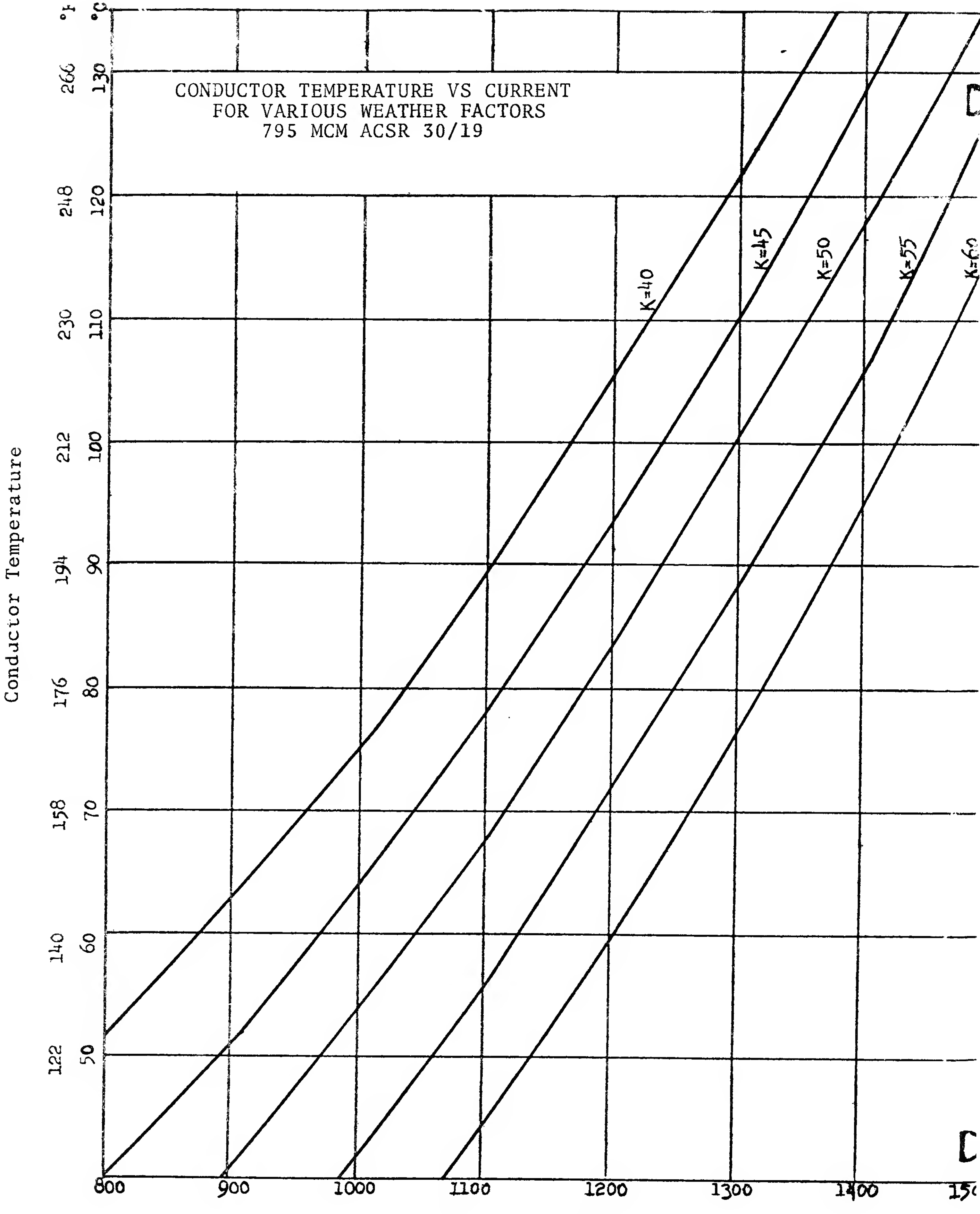
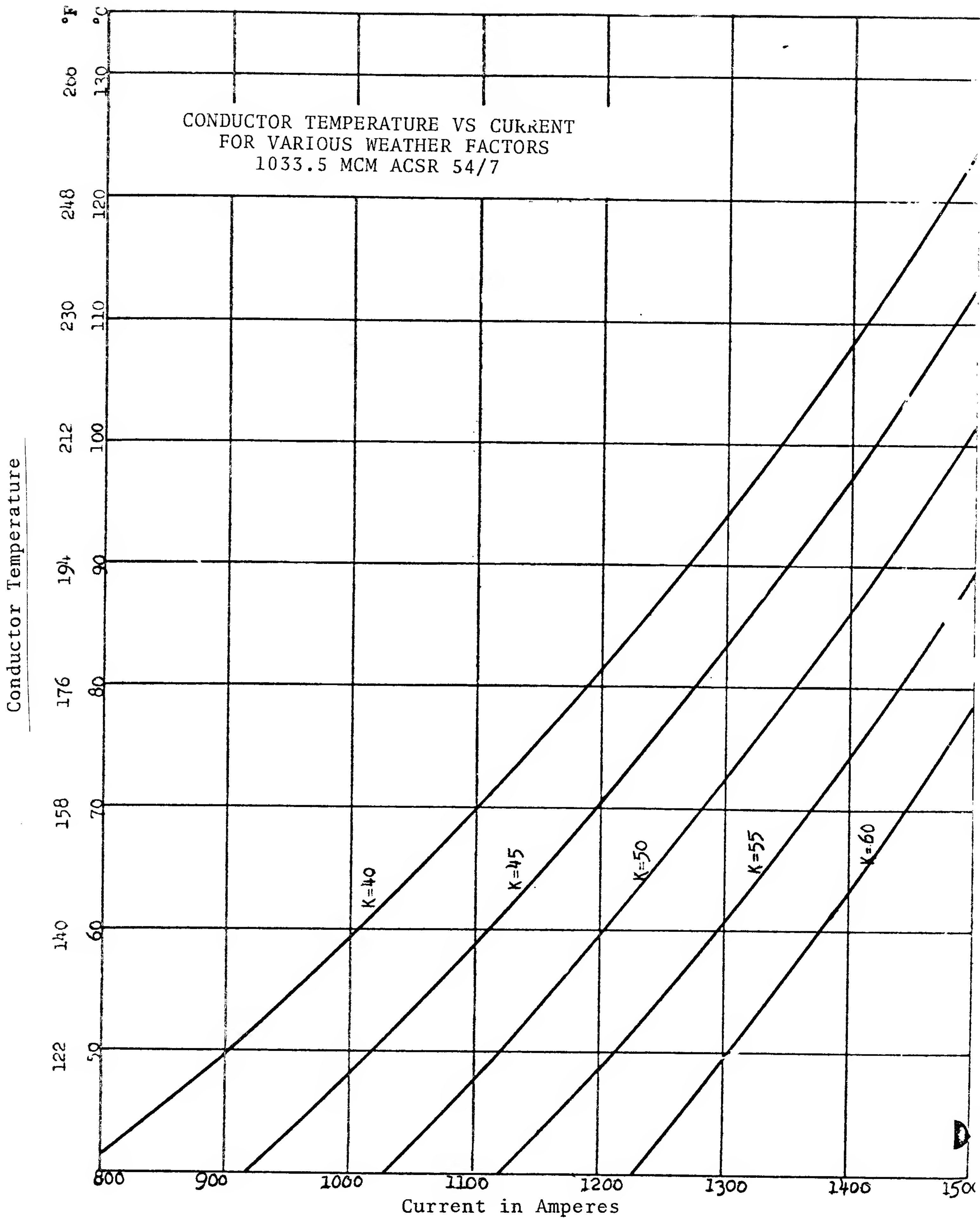

CONDUCTOR TEMPERATURE VS CURRENT
FOR VARIOUS WEATHER FACTORS
795 MCM ACSR 30/19
°F
°C
266
130
248
120
230
110
212
100
194
90
176
80
158
70
140
60
122
50
Conductor Temperature
K=40
K=45
K=50
K=55
800
900
1000
1100
1200
1300
1400
Current in Amperes

Figure 4


CONDUCTOR TEMPERATURE VS CURRENT
FOR VARIOUS WEATHER FACTORS
1033.5 MCM ACSR 54/7
Conductor Temperature
°F
°C
266
248
230
212
194
176
158
140
122
130
120
110
100
90
80
70
60
50
K=40
K=45
K=50
K=55
K=60
800
900
1000
1100
1200
1300
1400
1500
Current in Amperes

Review of 220 kv Lines

All existing 220 kv lines on the PP&L Co. system were reviewed by the Transmission Division to establish a maximum conductor temperature under which each line could safely operate. This maximum temperature is dictated by one or more of the following items:

1. Reduction of conductor mechanical strength due to annealing.

2. Increase in sag at higher temperatures causing either reduced ground clearances or reduced clearance to foreign facilities.

3. Localized heating in magnetic type clamps.

4. Localized heating in compression splices and dead end assemblies.

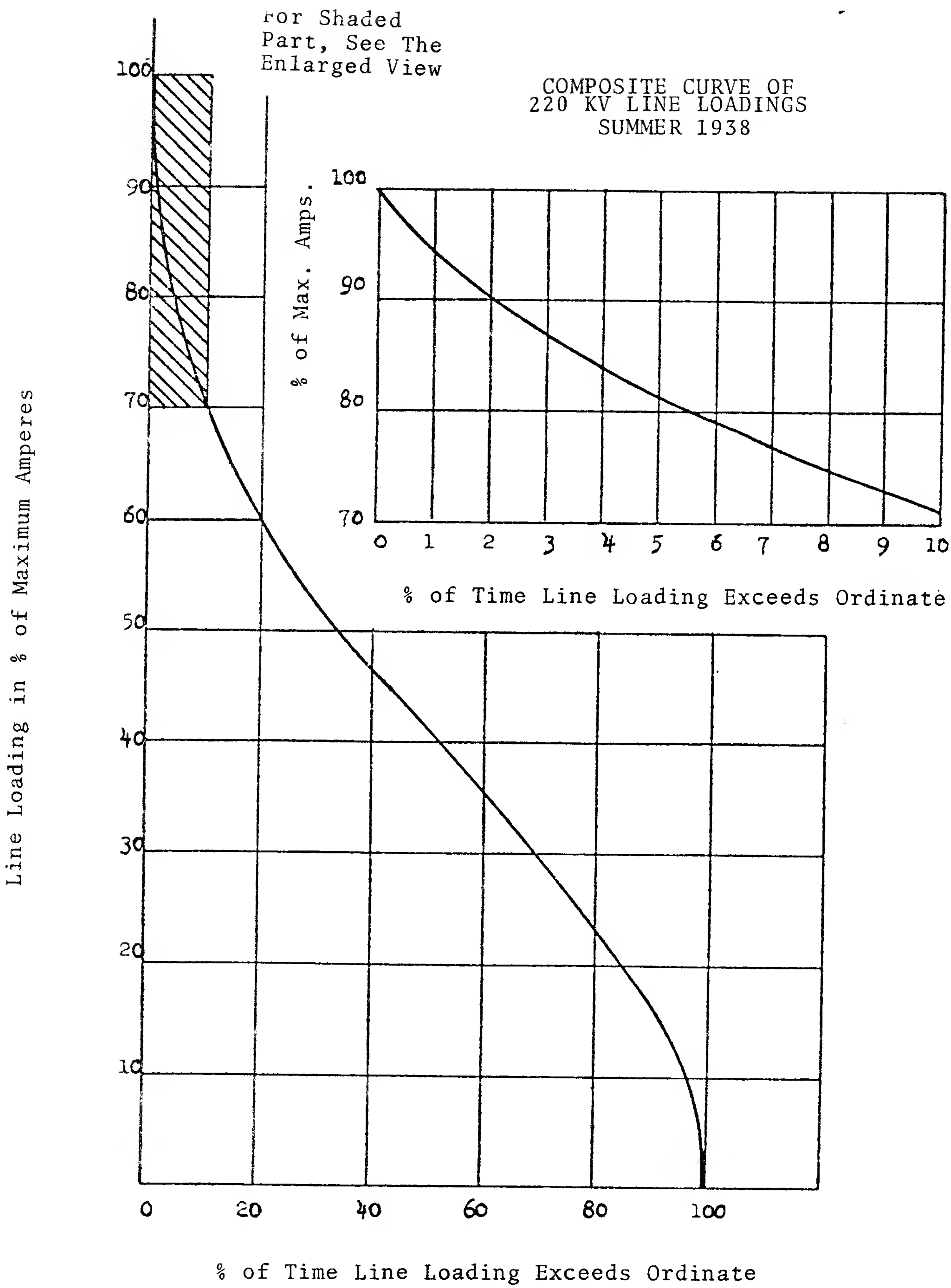
With these factors in mind, a review of the 220 kv lines indicated that recently constructed and all future lines under present design conditions may be operated at 93 C (200 F) continuously, or at 125 C (257 F) for a maximum of 10,000 hours.

The 795 Mcm ACSR conductors having 54 aluminum and 7 steel strands on the original Wallenpaupack-Siegfried line are stressed to 63.2% of their ultimate strength under a mechanical load of 1" of ice in the southern section or 1-1/2" of ice in the northern section and a wind pressure of 8 lbs per square ft. This conductor is stressed too high to allow any loss of strength due to annealing. Suspension clamps are of the magnetic type and no armor rods are installed. In order to operate at 93 C (200 F) it would be necessary to (1) improve ground clearances to meet minimum standards, (2) install non-magnetic type suspension clamps and armor rods, and (3) take corrective measures to insure no localized heating in compression fittings and dead end assemblies.

Existing lines, other than the above-mentioned Wallenpaupack-Siegfried line located in loading districts of 1" radial ice or less may be operated at 93 C (200 F), with up to 10,000 hours of operation at 125 C (257 F) providing lines are equipped with non-magnetic clamps and armor rods and that ground clearances and utility clearances are adequate.

Existing lines located in loading districts of more than 1" radial ice may be operated to temperatures of 93 C (200 F) providing they meet the conditions as stated previously. Operation at higher temperatures is not recommended for existing lines in these severe ice loading districts.

General line data, together with specific recommendations for each line, the construction changes required to operate at higher temperatures, and the estimated cost of such changes, as prepared by the Transmission Division are shown on the summary sheet in Appendix II.


For Shaded
Part, See The
Enlarged View
COMPOSITE CURVE OF
220 KV LINE LOADINGS
SUMMER 1938
100
90
80
70
60
50
40
30
20
10
0
20
40
60
80
100
Line Loading in % of Maximum Amperes
% of Time Line Loading Exceeds Ordinate
% of Max. Amps.
0
1
2
3
4
5
6
7
8
9
10
% of Time Line Loading Exceeds Ordinate

Load Duration on 220 Kv Lines

The System Operating Dept. prepared load duration curves for various 220 kv and 66 kv transmission lines. These curves show the loading conditions (loading in amperes versus the cumulative per cent of load duration) for the winter of 1957-1958 and the summer of 1958. The line loading was obtained from station logs and is the average of the three phase currents for each line. The seasonal loading was based on loads for one week each from December, January, and February for the winter curves and one week each from June, July and August for the Summer curves. Dates were chosen when operating conditions for each particular line were normal.

By combining the available 220 kv summer line loading curves, a composite curve for the summer of 1958 can be derived. See Figure 6. A similar curve can also be derived for winter loading conditions.

The portion of this line loading curve of primary interest from a thermal standpoint is the loading from 75% to 100%. This part of the curve is shown in the enlarged view on Figure 6. The portion of the summer weather curve of primary interest from a thermal standpoint is that part from K = 40 to K = 50. This part of the curve has been expanded in order to obtain more accurate readings of duration and was shown in the enlarged view on Figure 3.

The probability of a low weather factor occurring simultaneously with a high line loading is the product of the probability of each occurring independently. From the conductor temperature information obtained for various ampere loadings from the IBM 650 computer, the maximum number of hours per year at operations greater than the minimum annealing temperature can be obtained.

DETERMINATION OF ANNEALING TIME
TYPICAL SUMMERTIME OPERATION
795 MCM ACSR

Amps	% of time	K 42.5	42.5-47.5	47.5-52.5	52.5-57.5	57.5-62.5
		0.9%	12.1%	9%	4%	4%
1250 to 1350	0.6%	.119 hrs at 123 C	1.60 hrs a 111 C	1.19 hrs at 101 C	.53 hrs at 89 C	.53 hrs at 77 C
1150 to 1250	1.5%	.298 hrs at 105 C	4.21 hrs at 94 C	2.98 hrs at 83 C		
1050 to 1150	2.2%	.437 hrs at 90 C	5.9 hrs at 78 C			

The total hours of operation which could be expected to occur during the summer months at temperatures in excess of the minimum annealing temperature is the sum of the hours listed in the above chart. This amounts to approximately 18 hours. Another 18 hours would be expected to occur during the winter months (if line ratings are increased accordingly), amounting to a total of 36 hours of operation per year at temperatures above the minimum annealing temperature.

Figure 7

13-- A 795 MCM

Determination of Conductor Annealing

The maximum operating temperature on the lines is dictated largely by clearance conditions and this in turn fixes the maximum amount of current which can be carried on the line. However, it is necessary to determine whether this maximum current will cause excess annealing under weather and loading conditions typical of PP&L system. By combining the composite loading curve of Figure 6 and the weather factor curve of Figure 3, the number of hours during which annealing can be expected to occur can be calculated. The method of doing so is illustrated in Figure 7. This figure is constructed specifically for a 795 Mcm ACSR conductor, but the same principle can be applied to any size or type conductor. Results indicate that a maximum of 18 hours of operation in excess of annealing temperatures could be expected to occur during a typical summer, if current is limited to the maximum allowed by clearance conditions. For a 795 Mcm conductor this is 1300 amps, and for a 1033.5 Mcm ACSR conductor the maximum current is 1500 amps. Similar load duration and weather factor distribution would occur during the winter months, but because of the lower ambients and higher wind velocities, the maximum current ratings can be increased to 1475 amps for a 795 Mcm ACSR conductor and 1675 amps for a 1033.5 Mcm ACSR conductor. Under these conditions, it can be safely said that another 18 hours of operation in excess of annealing temperatures could be expected to occur during a typical winter (November, December and January). This results in a total of some 36 hours per year. Since there is a 10,000 hour maximum allowable time for operation at 125 C, and since operation of a typical line indicates only 36 hours per year at temperatures between 80 and 125 C, it can be seen that the total life of the conductor is in excess of 300 years, well beyond the actual useful life of a transmission line. It may be practical to design the clearances on future circuits to bring the annealing characteristics of the conductor more closely into line with the useful life of the circuit.

Terminal Equipment in 220 kv Substations

Appendix III lists the existing terminal equipment and its name plate rating for each line terminal at all existing 220 kv substations. Also included is the existing and ultimate capability of the connected transmission line under summertime operating conditions. If any of the terminal equipment restricts the operation of a transmission line from its existing or ultimate capability, this is so noted and an estimated cost is given to remove this terminal equipment limitation.

The following general considerations concerning substation terminal equipment should be noted:

1. With a few exceptions, connectors, terminals and equipment in 220 kv substations are as good as, or better than, their connecting transmission conductors from a thermal standpoint. However, in order to operate at higher temperature levels, all connectors, terminals, air break switch and CCB contacts must have adequate contact pressure to prevent overheating.

2. Air break switches which are normally rated at 1200 amps are considered capable of carrying 1300 amps continuously, 1500 amps for periods up to 3 months and 1650 amps for periods up to 2 days. Switches should be inspected at the first opportunity after carrying more than 1300 amps and contacts cleaned and adjusted accordingly. If this is done, high current operations, as stated above, can be repeated on these switches.

3. In all cases where the primary circuit of a current transformer is overloaded, all current coils in the secondary circuit should be checked in order to avoid pinning of indicators for switchboard meters, to prevent overloading of relays, varmeters and wattmeters, and to maintain interconnection metering accuracy. In these respects, each terminal is different and must be considered on its own merits. From a thermal standpoint, little information is available concerning the overload capability of bushing current transformers; however, it is doubtful that bushing current transformers would be a limiting factor.

4. In general, if the terminal equipment coordinates with the summertime capability of the transmission line, it will coordinate with the wintertime capability, provided current coils in the current transformer secondary circuits have been checked as described previously.

5. If a transmission line terminates in a transformer (such as at So. Akron or West Shore), it is the transformer which restricts the maximum capability of the line.

<u>Summary</u>

By taking advantage of the thermal capability of 220 kv lines and substation terminal equipment as determined in this report, 220 kv lines can carry currents one and one half times those presently specified in conductor handbooks.

The operating temperature for six of the 13 existing 220 kv lines on PP&L Co. system is limited to 49 C (120 F) due to the ground clearances which were specified by former design conditions. This limits the current to 775 amperes in the summertime and 1050 amperes in the wintertime.

Construction changes as specified in Appendix II and III would be necessary to take maximum advantage of the thermal capability of these existing 220 kv transmission lines and terminal facilities.

7/6/60
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INSTRUCTOR'S GUIDE

CASE TITLE: Steady State Thermal Ratings for 220 KV Overhead Conductors

RELATED UNDERGRADUATE CURRICULUM AREAS:

1. Thermodynamics.
2. Heat Transfer.
3. Power Systems Analysis.
4. Engineering Analysis

SYNOPSIS: High voltage transmission lines are not normally limited by voltage drop considerations but rather by the increase in temperature of the wire resulting from the I^2R losses. This case study describes the approach taken by two engineers in the Pennsylvania Power and Light Company. At first glance, the problem would appear to be simply the determination of the heat loss from an infinite cylinder with internal heat generation. However, the exercise of considerable engineering judgment was required to analyze the effects of the most severe weather conditions and the loss of strength due to annealing in the composite wire.

The significant increase in current carrying ability of the existing company lines resulting from this study has deferred the need for new transmission lines and postponed substantial capital expenditures.

QUESTIONS FOR THOUGHT AND DISCUSSION

After reading Part A:

1. What method or equation would you recommend to evaluate the heat loss from an infinite cylinder with internal heat generation under outdoor conditions?

2. What information would you need to obtain to evaluate the heat loss?

3. Discuss the pros and cons of exceeding the annealing temperature under emergency conditions.

4. Read the two papers in Part B, references 1B and 2B, including the discussion following the second paper. Discuss. At this time questions 1, 2 and 3 should be reconsidered and comparisons made.

After reading Part B:

1. What do you think are the reasons that led Ed and Jack to use the relationship presented in the article by Mr. Enos?

2. The equation used to determine the heat loss is for the forced convection case. How was the condition of very low wind speed handled?

3. When a conductor is operated at high temperatures, what factors must be considered? Analyze a homogeneous and a composite material to appreciate the difference.

4. Read Ed Reis's report, reference 3B. On page 27B the method employed for the determination of conductor temperature is outlined. Using the following information for 795 Mcm ACSR conductor

   conductor outside diameter = 1.40 inches
   conductor ac resistance = .117 (1 + .00403 (T_C - 25C)) ohms/mile

   a. Calculate the ambient temperature corresponding to several values of K between 40 and 60.

   b. Write a computer program to obtain the data for the curves on page 28B (note that K does not remain a constant on each curve).

   c. Devise an alternate method of obtaining the curves on page 28B and compare. A suggestion is given below and on the following page:

      i. Assume a reasonable value of ambient temperature, calculate the wind speed for a given value of K.

ii. $I^2R = K = g(Tc)$, (V, Ta & D known)

$$I^2 = \frac{K}{R} = \frac{g(T_c)}{f(T_c)} = h(T_c)$$

vary T_c and obtain I.

5. Discuss the pros and cons of ignoring solar and back radiation.

6. Clearly identify the times during the project where engineering judgment was exercised.